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CHINESE EXPERIENCES
IN MINI-HYDROPOWER GENERATION

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
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Small Hydropower Series No. 3

CHINESE EXPERIENCES IN MINI-HYDROPOWER GENERATION

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China

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EXPLANATORY NOTES

The basic monetary unit in China is the yuan renminbi (¥RMB) and its principal fractional unit the fen (¥RMB 1 = 100 fen).

Preface

Decentralization of hydropower generation has become one of the accepted means of developing energy resources to meet rural energy requirements and support programmes of rural industrialization and decentralization of industry in developing countries.

UNIDO organized the Second Seminar-Workshop/Study Tour in the Development and Application of Technology for Mini Hydropower Generation (MHG), held at Hangzhou, China, from 17 October to 2 November 1980, and Manila, Philippines, from 3 to 8 November 1980. One of the objectives of the Seminar-Workshop/Study Tour was to promote the exchange of experiences in the planning, construction and application of mini-hydropower generation units in developing countries, and in particular to learn the methods of planning and programme implementation applied in China.

The Chinese delegates at the meeting presented a number of papers on mini-hydropower generation in China. However, many participants have asked UNIDO for more information on Chinese experiences in that field. UNIDO therefore requested the Chinese authorities to prepare this manual. It was decided that the first edition of the manual should be subject to regular modification and improvement based on suggestions submitted by readers.

The manual is designed to complement the previous UNIDO publication entitled "Mini-hydropower stations; A manual for decision makers" (ID/SER.N/1). Its preparation, made possible by a contribution of the Government of China to the United Nations Industrial Development Fund, was mainly the work of:

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UNIDO hopes that the manual will serve as a practical and useful tool in planning mini-hydropower generation in developing countries.

ABSTRACT
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CHINESE EXPERIENCES IN MINI-HYDROPOWER GENERATION

SERIE : PETITES CENTRALES HYDROELECTRIQUES, N° 3

EXPERIENCE CHINOISE DANS LE DOMAINE DE L'IMPLANTATION DE PETITES CENTRALES HYDROELECTRIQUES

SERIE PEQUEÑAS CENTRALES HIDROELECTRICAS No. 3

EXPERIENCIAS CHINAS EN PRODUCCION DE ENERGIA HIDROELECTRICA CON PEQUEÑAS CENTRALES

ABSTRACT / SOMMAIRE / EXTRACTO

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ABSTRACT

In line with its national policy of rural industrial development, China has for many years pursued an active programme of mini-hydropower generation to meet the energy needs of rural areas, particularly isolated areas cut off from the national power grid.

This study describes Chinese experiences in this field. It deals with policies and measures, economic issues, technical problems of exploitation and design, production of machines and equipment, promotion of research and development, manpower training and other important aspects of the promotion and implementation of mini-hydropower projects.

SOMMAIRE

En application de sa politique nationale de développement industriel des zones rurales, la Chine, depuis de nombreuses années, poursuit activement un programme d'implantation de petites centrales hydroélectriques devant permettre de satisfaire les besoins énergétiques des zones rurales, notamment celles qui sont isolées du réseau national de distribution.

La présente étude décrit l'expérience de la Chine dans ce domaine, les politiques et les mesures adoptées, les aspects économiques, les problèmes techniques de conception et d'exploitation, la fabrication des machines et de l'équipement, la promotion de la recherche-développement, la formation de la main-d'oeuvre et les autres questions importantes que soulèvent le lancement et la réalisation de projets concernant les petites centrales hydroélectriques.

EXTRACTO

De conformidad con su política nacional de desarrollo industrial del campo, China lleva muchos años aplicando un activo programa de producción de electricidad con pequeñas centrales hidroeléctricas para satisfacer las necesidades de energía de las zonas rurales, en particular de aquellas zonas aisladas no conectadas a la red eléctrica nacional.

El estudio describe las experiencias chinas en este ámbito y trata lo relativo a las políticas y las medidas, los aspectos económicos, los problemas técnicos de la explotación y el diseño, la producción de maquinaria y equipo, el fomento de la investigación y el desarrollo, la capacitación de la mano de obra y otros aspectos importantes del fomento y la realización de proyectos de pequeñas centrales hidroeléctricas.

CONTENTS

Tables

Figures

INTRODUCTION

China has rich water resources with a total potential capacity of approximately 680,000 MW, of which 370,000 MW may be feasibly exploited. The geographical features of China are characterized by high lands in the west and low lands in the east. Most of its main rivers originate in the western plateaux. Precipitation is abundant in southern China, hydropower resources being richer there in comparison with the northern area, where precipitation is quite low.

In 1979 coal ranked first as an energy source in China, petroleum was second and water, which accounted for only 17 per cent of total energy production, came last. Hydropower generation currently involves only about 5 per cent of total water resources. The potential for future development is therefore great.

The definitions of small hydropower generation, mini-hydropower generation and micro-hydropower generation vary among different countries and organizations, as reflected in table 1.

In China hydropower plants with a total installed capacity of up to 12 MW, units of less than 6 MW and small local grids are classified as small hydropower generation facilities. However, in order to avoid confusion, the term mini-hydropower generation (MHG) will be extended to cover such facilities in this publication.

A. Development and construction of MHG stations

Water power is a cheap, clean and renewable energy resource. Since 1949 the Government of China has attached great importance to the development of MHG. Up to the end of 1979, China constructed more than 89,000 MHG stations with a total capacity of approximately 6,300 MW.

The annual energy output by MHG in 1979 was 11,900 GWh, or approximately 35 per cent of electricity consumption in agriculture. By 1979, 1,500 out of a total of approximately 2,000 counties had established their own MHG and nearly 700 counties relied mainly on MHG for supplying electricity to industry and agriculture.

The construction of MHG stations in China was initiated on the basis of a nation-wide movement in agricultural co-operation conducted in the early 1950s. Rural areas remain comparatively underdeveloped within the economy as a whole. A huge amount of electric power is needed for the development of industrial and agricultural production. It was difficult to meet the short-term needs of rural areas, and even impossible to do so in the remote rural regions, by merely relying on large- and medium-scale power stations built through government investment.

Full utilization of the scattered small hydropower potential in combination with water utilization for other purposes is ensured by constructing power stations to meet local electricity demand. There are many stations, each covering certain areas, scattered throughout the country. A local network was formed and connected to the government-run grid. This should help meet demand in rural areas for electricity and promote a quicker development of agriculture with less government investment.

Table 1. Classification of hydropower stations according to power capacity

Country or organization	Micro-hydropower generation (kW)	Mini-hydropower generation (kW)	Small hydropower generation (kW)
China			
By unit			Up to 6 000
By installed capacity			Up to 12 000
Peru	5-50	51-500	500-5 000
Philippines			Up to 5 000
Romania			5-5 000
Sweden			100-1 500
Thailand		Up to 1 000	
Turkey	0-100	101-1 000	1 001-5 000
United States of America			Up to 15 000
UNIDO			
Kathmandu seminar a/	Up to 100	100-1 000	
Hangzhou-Manila seminar b/	Up to 100	101-2 000	2 001-10 000
Preparatory Committee for the United Nations Conference on New and Renewable Sources of Energy (Panel on Hydropower)	Up to 1 000		1 001-10 000

a/ Seminar-Workshop on the Exchange of Experience and Technology Transfer on Mini Hydro Electric Generation Units, Kathmandu, Nepal, 10-14 September 1979.

b/ See preface.

In China, the development of MHG has been rapid and may be roughly divided into three stages: the total annual installed capacity was only several thousand kilowatts during the 1950s, tens of thousands of kilowatts during the 1960s and several hundred thousand kilowatts during the 1970s, approaching 1 million kW by 1979. At the current stage of technological development in China, the construction of a MHG plant with an installed capacity of several thousand kilowatts takes about two years, from the beginning of construction to the commissioning of its first unit. The design capacity of projects being implemented should be more than three times the total installed capacity in the same year, that is, if the total installed capacity in one year is 1,000 MW, the design capacity of projects being implemented in the same year should be approximately 3,000 MW.

MHG production costs are rather low, amounting to approximately 2-3 fen per kWh, whereas the production cost of the small thermal coal or diesel-fuel power stations is about 10 fen or more per kWh.

B. Role of MHG in the economy

In recent years, as the result of a large-scale construction programme, MHG has played a very important economic role. Its advantages are described below.

MHG promotes the efficient use of water resources for farmland, thus creating conditions for rapid development in agriculture. Wherever there is MHG, irrigation can be rapidly developed and the means of protection against floods and droughts improved. For example, in Enping County, Guangdong Province, the Jinjiang river cascades have been harnessed and 130 MHG stations with a total capacity of 36 MW built. Drainage and irrigation improved rapidly thanks to the power supplied by MHG. At present, all 18,670 ha of farmland along both banks of the Jinjiang river are irrigated and the 8,000 ha of low-lying farmland previously threatened by water-logging have been changed into stable and high-yield farmlands, regardless of flood and drought.

The economical power supplies produced by MHG have furthered the development of county- or commune-operated industries. In many mountainous regions the availability of MHG led to the establishment of industries in such branches as agricultural machinery, cement, fertilizers, paper, textiles and food. For example, an installed power capacity of 18,000 kW is currently available as a result of MHG in Hendong County, Hunan Province. In 1979, the annual energy output was 70 GWh. Total industrial output is several times higher than it was before the introduction of MHG.

On the other hand, the development of local industry speeds up the exploitation of MHG. Local factories usually run by the county manufacture major MHG equipment and also do the maintenance and repair work. Thus, the development of MHG is interrelated with that of industry at the local level.

MHG contributes to the accumulation of funds for development. An MHG Station on an irrigation canal in Sichuan Province, with an installed capacity of 6,400 kW, has had a yearly income of 1,940 thousand Yuan renminbi (¥RMB) since it was commissioned. An MHG station in Hubei Province, with an installed capacity of 2,400 kW, took only four years to recover its initial investment. The Dafeishui MHG station in Sichuan Province has an installed capacity of 5,000 kW. Over the last nine years it has had a total income of 10,270,000 ¥RMB, several times the original capital investment.

MHG promotes the development of rural electrification and mechanization. Power supplied by MHG also enriches and promotes the cultural life of the people and speeds up the construction of new villages.

In short, the development of MHG has a promising future in China. MHG can supply most of the energy consumed by villages and towns in regions with abundant water power resources. However, the rate of increase in power supplies cannot match the increasing demand for electricity to help meet social needs and improve living standards, and there is still much room for improvement in the operation and management of MHG stations. The potential of the installed equipment has not yet been fully utilized in some places because the construction of transmission lines and substations has lagged behind the construction of the MHG station. Such problems must be solved in the near future.

I. ORGANIZATION AND PLANNING

The organizational units involved in MHG in China are shown in table 2.

A. Project development

The stages involved in the development of MHG projects are outlined below.

River planning

River planning should be carried out by the central Government, the province, the prefecture or the county, depending on the importance of the river. If the river is the concern of more than one province, the planning works should be undertaken by the Ministry of Water Conservation. If the river is located within one province but involves more than one prefecture, the planning works should be done by the provincial bureau of water conservation. The same principle is applied to river planning for a small river located within a prefecture or county.

The river planning report should include medium- and long-term development plans and cover the first stage of implementation of the project. The prefeasibility study is also a part of this stage.

Design

After approval of the river planning, the design work for the first stage of the project should be continued. MHG projects usually involve two steps, namely preliminary design and detail drawing.

With regard to preliminary design, the design work of a small MHG project is commonly undertaken by the county. Approval of the design of the MHG project is given at the provincial level when the unit capacity is greater than 500 kW (or the transmission line has a voltage of 35 kV or more), and at the prefecture or county level when the unit capacity is less than 500 kW.

The main considerations in approving the design are social demands, the capabilities of the national, provincial or local authorities, and economic benefits.

The detail drawing should be undertaken by the county if the unit capacity is less than 500 kW. MHG projects with rather large unit capacity should be undertaken by the prefecture or province design institute.

After approving the preliminary design, the planning committee decides whether the project should be listed in the budget of the current year or the following one. Construction of this project can then be started.

Construction

A county MHG station with a capacity of greater than 500 kW should be organized by the county and supported by a professional team from the prefecture or province.

A county MHG station with a capacity of less than 500 kW should be organized by the commune or brigade and also supported by a professional team from the prefecture or province.

Field organization involves the local work-force and a professional team consisting of engineering, installation and transmission line technicians from the province or prefecture.

Table 2. Organizational units involved in MHG in China

Level	Organization in charge of water conservation	Organization in charge of MHG
Central Government	Ministry of Water Conservation	Department of Farm-land Water Conservation, Division of Hydropower
Provincial government	Bureau of Water Conservation	Division of Hydropower
Prefectural authority	Department of Water Conservation	Division of Hydropower
County government	Division of Water Conservation	Hydropower unit, MHG company

Note: The county-level hydropower unit usually is the grass-roots office dealing with the design, construction, operation and maintenance of MHG stations. Many counties now have a total installed capacity of 10-20 MW and distribution lines several hundred kilometres in length.

Operation and maintenance

Operational regulations and records are established in each MHG station. Maintenance and minor repairs may be undertaken by the county. Major overhauls should occasionally be done by the prefecture.

B. Policy guidelines

The Government of China and the authorities concerned have established a series of policies for the development of MHG, the elements of which are summarized below.

Dependence of MHG development on the masses

The self-reliance of the masses in the development of MHG should be stressed. The counties, people's communes and their subdivisions are encouraged to develop MHG, according to the principle of "whoever invests in and builds a station will own, manage and benefit from it". If the MHG station is invested in and jointly built by several organizations, it will be owned by them. This policy has proved more than once to be a faster, better and more economical way to expedite the development of MHG.

Sources of finance

The sources of financing will mainly be local organizations at different levels and government subsidies usually amounting to approximately 30 per cent of total investment.

In order to expand the role of loans, the Sichuan Provincial People's Bank has laid down the following five requirements to be met when applying for a loan:

(a) The project design and budget must be prepared and approved by the relevant authority and listed in the construction items for the current year;

(b) The supply of power units and the main construction materials must be confirmed by the departments concerned;

(c) It must be possible to commission the MHG station during the current year;

(d) Power must be available for transmission and consumption after completion of the MHG station;

(e) A certain amount of self-financing must be ensured.

If all the above-mentioned requirements are fulfilled, the loan will be granted.

Overall planning and multi-purpose utilization

The planning, geological exploration and design work for MHG must be carefully done and the construction closely supervised in order to ensure quality and efficiency of operation.

MHG must be based on a natural river system, on its hydrological and geological conditions and on load demands. The principle of overall planning and multi-purpose exploitation must be observed, attention being paid to co-ordination between the departments concerned and to the solution of problems relating to power generation, flood protection, irrigiation, navigation, fisheries and log-moving.

The feasibility study and design report of a MHG plant with a unit capacity greater than 500 kW (including the corresponding substation and transmission line) must be approved by the Bureau or Department of Water Convervancy at the provincial level. The design document of a MHG plant with a unit capacity less than 500 kW must be approved by the Department of Water Conservancy at prefectural or county level. If the MHG project concerns two provinces, counties, communes or brigades, an agreement between the two sides must be attached to the document.

A MHG station cannot be listed among the construction items for a given financial year unless the design document is approved.

Supply of raw materials

A MHG unit, with a capacity of less than 500 kW, is usually manufactured by a local factory. A certain amount of the raw materials are supplied by the central Government, but the remaining materials must be provided by the province or municipality. Power units, with a capacity of greater than 500 kW, are manufactured and controlled by the central Government in accordance with the plan. In China, in order to simplify the procedures of supply and to speed up the construction schedule, equipment for MHG must be supplied by the manufacturer in complete sets.

Integration into the national grid

Priority has been given to local consumption of energy produced by MHG. In order to give full play to MHG and to improve the reliability of the power supply, MHG plants may be gradually integrated to form a local grid, and eventually integrated into the national grid when the necessary conditions are satisfied.

The operation, ownership and administration of a MHG plant remain unchanged following an integration agreement. Both the national and the local grid have the responsibility of giving active support to the integration of MHG stations. If operation of the grid is interrupted, the MHG stations may be operated independently.

II. ECONOMIC FACTORS

The special economic features of MHG in China are as follows:

(a) The construction period is short and the results are quick;

(b) Local materials and labour are fully utilized;

(c) Equipment is domestically and even locally manufactured when the unit capacity is less than 500 kW.

Because of the large size of China, local conditions differ widely from region to region, with the capital cost of MHG ranging from 500 to more than 2,000 MB per kW. In general, the cost is 1,000-1,300 MB per kW.

The technical and economic features of 25 MHG plants built during the 1960s and 1970s in various locations are presented in tables 3, 4 and 5 (the water head ranges from 4.5 to 612 m and the installed capacity from 150 to 12,000 kW). The cost breakdown for the different MHG stations is affected by the differing lengths of the transmission lines. A breakdown of total costs produces the following range of values: civil engineering, 42-65 per cent; equipment, 31-48 per cent; transmission lines, 4-14 per cent.

A. Comparison of alternative energy sources

In the exploitation of the energy resources of China, top priority is given to meeting the requirements of the agricultural sector. In this section a comparison will be made between different sources of energy.

For an economic comparison between different energy sources total investment and annual operation costs are usually taken as a whole. At present, the method of "years for compensation" is generally adopted. When the total investment Z_1 of alternative 1 is greater than Z_2 of alternative 2, and the annual operation cost F_1 of alternative 1 is lower than F_2 of alternative 2, a comparison can be made by calculating N (years of compensation).

$$N = \frac{Z_1 - Z_2}{F_2 - F_1} \qquad (1)$$

After N is obtained, other factors such as the availability of a local source, technical status and economic ability of the investor etc. must be taken into account. N usually amounts to about 10 years.

In China, alternatives to MHG for rural electrification include small thermal power stations or diesel generation and an extension of the existing regional or state grid.

Biogas, geo-thermal and wind power generation can also be considered according to the local conditions.

Small thermal generation

The capital cost and operational expenses of a newly-built small thermal power station are shown in tables 6 and 7.

Table 3. Technical and economic analysis of MHG plants (diversion-type)

Plant name	Location (province)	Design discharge (m^3/s)	Maximum head (m)	Average head (m)	Total installed capacity (kW)	Total cost (thousands of ¥RMB)	Average annual utilization (h)	Cost per kW (¥RMB)	Cost per kWh (¥RMB)	Cost of generation (fen/kWh)
Zhangwangmao	Jiangxi	64	10	8.44	2 x 1 250	4 780	4 800	950	0.19	2.61
Yongan	Sichuan	63	11	10.0	3 x 1 250 3 x 250	6 650.88	7 989	1 498	0.19	1.194
Tonglienyen	Jiangxi	8.88	22.9	22.4	1 760	1 300	4 215	730	0.28	2.5
Tongkouqi	Zhejiang	4.0	48.4	46.9	2 x 800	1 661	2 000	1 038	0.27	3.8
Yaqi	Zhejiang	11	51.6	50.4	4 450	6 500	3 120	1 460	0.46	1.0
Tangshaoshui	Jiangxi	2.5	56	55	1 x 200 1 x 800	1 103	4 716	1 100	0.24	3
Minyangkuan	Jiangxi	4.2	76	75	2 x 1 250	2 660	3 670	1 064	0.27	2
Tongyuan II	Jiangxi	3.6	80	80	2 x 630	1 090	2 822	860	0.27	2.5
Kenghuang	Zhejiang Guangxi	0.32	94.6	93.6	200	198.3	2 500	992	0.4	3.8
Xixiankou	Zhaung Autonomous Region	3	132	130	2 x 1 600	2 600	3 150	813	0.26	2.5
Datian	Zhejiang	1	181	181	3 x 400	875	5 000	729	0.146	2.5
Chongshan	Hunan	0.6	210	210	4 x 250	876.6	3 360	876.6	0.26	3
Jiangkou	Hunan	0.28	612	612	2 x 500	840	1 200	840	0.11	1.5

Table 4. Technical and economic analysis of WHG plants (dam-type) a/

Plant name	Location (province)	Design discharge (m^3/s)	Maximum head (m)	Average head (m)	Total installed capacity (kW)	Total cost (thousands of ¥RMB)	Average annual utilization (h)	Cost per kW	Cost per kWh	Cost of generation (fen/kWh)
Yangtang	Hunan	6.8	5.5	4.5	6 x 1 500 4 x 252	20 900	4 334	2 090	0.484	1.2
Qingshan	Zhejiang	21.8	13	10.9	4 x 500	2 050	2 500	1 025	0.34	1
Dalongdong	Guangdong	12	25	20	2 000	2 389	4 380	1 195	0.27	2
Maoqi	Hunan	20	45	36	4 x 1 250	7 610	3 920	842	0.2	1.2
Yangwotan	Hunan	12	50	43.75	1 x 3 200 2 x 3 000	800				
Kaofeng II	Hunan	4 x 0.48	136	136	4 x 500					
Kaofeng I	Hunan	3 x 0.77	219	202.5	3 x 1 250	3 219	5 450	556	0.102	2.1

a/ Power-house at downstream side of dam.

Table 5. Technical and economic analysis of MHG plants (run-off-type and composite-type)

Plant name	Location (province)	Type of plant	Design discharge (m^3/s)	Maximum head (m)	Average head (m)	Total installed capacity (kW)	Total cost (thousands of ¥RMB)	Average annual utilization (h)	Cost per kW (¥RMB)	Cost per kWh (¥RMB)	Cost of generation (fen/kWh)
Chenjiang	Zhejiang	Run-off	10.8	4.5	4.25	4 x 75	406	5 500	1 353	0.24	3
Xutang	Zhejiang	Run-off	3.9	5.7	5.5	2 x 75	276.3	5 225	1 841.9	0.36	1.9
Chenguan	Hunan	Run-off	13.68	5.125	4.125	8 x 500	5 514.7	6 150	1 400	0.207	2.5
Ganqi	Hunan	Run-off	16.9	11.6	10.5	10 x 1 250	20 053	6 150	1 600	0.26	0.9
Tongkengqi	Zhejiang	Composite	0.5	150	136	2 x 500	990	3 500	990	0.33	4.83
Tongbai	Zhejiang	Composite	3.4	310	300	2 x 4 000	12 500	4 144	1 563	0.3	2.5

Table 6. Cost of a newly-built small thermal power station

Capacity of station (kW)	Total cost (thousands of ¥RMB)	Cost breakdown: Equipment (percentage)	Civil works (percentage)	Installation (percentage)	Miscellaneous	Cost (¥RMB/kW)
2 x 750	1 500	65	71	10	8	1 000
2 x 1 500	2 700	60	24	8	8	900
2 x 3 000	5 040	60	24	8	8	840
2 x 6 000	8 760	58	26	8	8	730

Table 7. Operational expenses of a small thermal power station

Capacity of station (kW)	Depreciation, charge of material and spare parts (¥RMB/kW)	Wages, overheads (¥RMB/kW)	Number of employees per MW generated	Domestic power consumption (percentage)	Coal consumption (kg/kWh)	Cost (¥RMB/kW)	Peak-load utilization (hours per year)	Cost of generation (¥RMB/kWh)
1 x 750	97.3	47.3	70	14-15	1.17	1 200	1 500-2 000	0.144-0.120
1 x 1 500	87.5	40.6	60	11-12	0.875	1 080	2 000-2 500	0.099-0.086
1 x 3 000	81.8	30.4	45	10-11	0.625	1 010	2 500-3 000	0.069-0.062
1 x 6 000	71.0	16.9	25	8-9	0.578	876	3 000-3 500	0.051-0.047

Small rural thermal power stations are usually built near a town or in a region where fuel can be easily obtained and where water resources are unavailable or far from the state grid. A coal-burning thermal power station should be built where indigenous coal is available. A shortage of indigenous coal or its long-distance transport would substantially raise the cost of generation.

Compared with MHG stations, the operation and management of a small thermal power station is rather complicated. The cost of generation is higher (8-15 fen per kWh) and will be affected by coal prices. The adaptability of the load change is poor. Pollution from a small thermal plant can also be rather serious. Such unfavourable factors must be taken into account before building a small thermal power station.

The exploitation of MHG stations can save coal fuel and supply cheap power. A hydropower plant with a regulating capacity can play an important role in taking away some of the burden during peak-load. The shortcoming of MHG is power deficiency in the dry season, but the construction of small thermal plants can make up this deficiency and thus imp[illegible]ve the reliability of the power supply.

Small diesel generation

In China the capacity of diesel power stations is usually less than 100 kilowatts. They have been primarily built in smaller towns and in small factories, mines and other enterprises. The capital cost of a diesel station (about ¥RMB 500-600 per kW) and its domestic consumption are low. The starting and shutting-down of a diesel station is rather simple and requires only a small number of operators. However, because of the level of diesel consumption, the cost of generation is rather high. A higher level of technology in operation and management is also required. As a result, only in cases where the load is not heavy, the load centre is far away from the coal mine or grid, and hydraulic sources are not available in nearby regions or only serve as an interim power source, should a diesel power station be built.

Extension of grid

The power supply from an existing regional or state grid may be more reliable and of better quality because grids have sufficient capacity to supply power to rural areas. This makes them more adaptable for regions where the load demand rapidly increases. In rural areas with a nearby grid, without water power resources and where demand is high, the power supply must therefore depend upon the extension of the grid. However, owing to the limited capacity of the existing grids, it will be difficult to [illegible]t scattered rural load demand in the near future. Moreover, long t[illegible]ssion lines are required to feed distant rural villages and the construc[illegible] new medium- or large-scale power plants will need larger government [illegible]tment than MHG. The construction period for the plants is also longer than for MHG. In short, MHG offers the following advantages: less government investment and shorter construction time; full utilization of the scattered water potential; suitability for distribution to widely dispersed rural villages; and the combination of MHG with water uses for other purposes. Such advantages should encourage local authorities to promote the development of MHG to the fullest extent possible. Connecting MHG plants into a network or an integration of MHG plants with the regional or national grid is recommended in order to utilize water-power fully. From the point of view of uninterrupted power supply for the promotion of agricultural production, the integration of MHG is a viable measure.

Biogas generation

Statistics have shown that the capital cost of biogas generation, which is only ¥RMB 400-500 per kW, is lower than that of MHG. Equipment and technology for biogas generation is rather simple and can be done by most of the commune or brigade. However, biogas production is limited by conditions such as good sealing (the lowest temperature must be higher than 9°C) and the supply of raw materials. In some rural areas biogas is used for cooking but hardly ever for power generation. Low-capacity biogas generation of up to a few dozen kilowatts occurs in a few places.

Biogas is a sort of inflammable gas that contains mainly methane (55-70 per cent) and is produced from organic waste materials through a process of fermentation by anaerobic bacteria under certain conditions of temperature, acidity, alkalinity and airtightness.

An estimate of gas production from various materials is given in table 8.

Table 8. Biogas production rate

Material used	Biogas yield (m^3/day)
40-50 kg pig dung	0.2
Large buffalo dung	1-1.4
0.5 kg fresh herring	0.3
0.5 kg hay	0.12

The equipment currently used for biogas generation is generally refitted from diesel engines by simply putting a biogas-air mixer at the air inlet. It uses diesel oil as well as biogas. When biogas is the main fuel, only a small amount of oil is used at the beginning. Diesel consumption is increased when the biogas is insufficient or the supply of biogas interrupted.

Other energy sources

In China the exploitation of geo-thermal, solar and wind power remain in the experimental stage. A group of experimental underground hot-water-power stations have been built. The temperature of water used in the stations is less than 100°C. At present, two approaches are used for generation, one involving an actuating medium with a low boiling-point, and the other involving pressure reduction and volume expansion.

There are two ways of generating electricity from solar energy. One converts solar energy first into heat, then into mechanical energy, and finally into electricity, and the other generates electricity directly from solar cells.

Electricity generated from wind energy is more suitable for grassland, pastoral areas, inshore islands and remote and windy mountain districts. A wind-energy generator has been installed on an inshore island and is being used to desalinate sea water.

The quality and quantity of solar- and wind-energy generation is affected by natural conditions which are a source of instability. An energy storage device such as a battery, although costly, would therefore be useful.

III. EXPLOITATION AND DESIGN

A. Design criteria

The following classification of hydropower projects and hydraulic structures is based on the classification and design standards of water conservation and hydropower projects and of hydraulic structures. In seismic regions, earthquake design standards for hydraulic structures are also applied.

Tables 9-12 are included for reference.

B. Planning

In planning a MHG station the main concerns are as follows: selecting the type of station; choosing the site and sequence of construction; deciding the scale of MHG; selecting the type of structures and the layout; comparing the alternatives for transmission and distribution lines; and estimating construction costs. The main points requiring study during the planning phase are described below.

Overall planning

A general investigation must be made of water resources, taking into account the development of local industry and agriculture and load demands. During planning the various departments concerned should co-ordinate their work, and the quantity of water available and the period of water consumption should be assessed. The various possible uses of the water, including flood control, irrigation, power generation, navigation, water supply for industrial and domestic use and fishery, should also be considered.

Feasibility of cascade development

Cascade development is based upon hydrological, topographical and geological conditions, distribution of farmland, mineral resources, water impounding and other technical and economic factors. In general, hydroplants with a storage dam are preferable for the upstream first cascade because the regulated inflow may improve power generation, irrigation, navigation and water supply.

Overall arrangement of MHG plants and major power plants and integration of MHG in the grid

Small hydropower plants in rural areas mainly supply electricity for agriculture, for irrigation and drainage, and for illumination. The major power plants provide electricity to industries run by communes or counties and to big electrical pumping and drainage stations. In order to make the power supply more reliable, it is advisable to set up a local grid to integrate the MHG plants, or to integrate the local grid into the state grid. When a grid is formed, the power from various sources can complement one another. If conditions permit, the MHG station may be operated to supply reactive power to the grid and thus improve the quality of the power supply.

Choosing the best alternative

Reliability and economy are the basic requirements for a project. The main power features of MHG are firm power, installed capacity, mean annual output etc. The main economic features are investment, running costs, profit etc.

Table 9. Classification of water conservation and hydropower projects

Grade of project	Scale of project	Gross reservoir capacity (millions of m^3)	Flood protection: Size of city, industrial or mining area	Flood protection: Farmland	Irrigation area (thousands of ha)	Installed capacity (mW)
I	Large (1)	>1 000	Very large	>333	>100	>750
II	Large (2)	1 000-100	Large	333-66	100-33	750-250
III	Medium	100-10	Medium	66-20	33-3.3	250-25
IV	Small (1)	10-1	Small	<20	3.3-0.33	25-0.5
V	Small (2)	1-0.1			<0.33	<0.5

Table 10. Classification of hydraulic structures

Grade of project	Grade of permanent structures Major structure	Minor structure	Temporary structure
I	1	3	4
II	2	3	4
III	3	4	5
IV	4	5	5
V	5	5	

Table 11. Period of flood recurrence for permanent hydraulic structures in normal operation

Grade of structure	Period of flood recurrence (years)
1	2 000-500
2	500-100
3	100-50
4	50-30
5	30-20

Table 12. Lower limit of flood recurrence for permanent hydraulic structures in abnormal condition (Years)

Type of dam	Period of flood recurrence for structures graded 1 to 5: 1	2	3	4	5
Earth dam, rock-fill dam, dry-laid rubble dam	10 000	2 000	1 000	500	300
Concrete dam, masonry dam and others	5 000	1 000	500	300	200

In addition to total cost, various unit costs are commonly adopted for investment comparison, such as unit costs per kW and per kWh, annual running costs (including depreciation of structures and equipment), overhauling and repair costs, maintenance cost, overhead expenses and wages.

A multi-purpose water conservation and hydropower project usually brings comprehensive benefits in flood control, irrigation, navigation, log driving etc.

The net income from power generation may be formulated as follows:

$$X_N = \sum_i (S_N)_i E_i \text{ (MB per year)} \quad (2)$$

$(S_N)_i$ = Net selling price per kWh (MB per kWh, obtained from selling price minus operating cost per kWh)

The symbol i denotes different users (the selling price for agriculture and industry are different).

E_i = Amount supplied to user i during a mean year (kWh per year).

The return period for the capital cost may be computed by the following formula:

$$T_R = \frac{Te}{X_N} \text{ (year)} \quad (3)$$

where T_e = Total investment

X_N = Net income per year

At present, T_R is usually 5-7 years, with an upper limit of 10 years.

T_R as an index does not reflect the feasibility aspects of an increment of investment. For example, in a hydropower plant of high head and low discharge, an increment of discharge may significantly increase the power output. Hence the feasibility of alternatives to trans-drainage-area water diversion is usually considered. The return period of the increment of investment for diversion of the drainage area flows is calculated as follows:

$$\Delta T_R = \frac{\Delta T_e}{\Delta X_N} \text{ (year)} \quad (4)$$

where ΔT_R = Return period of increment of investment, usually taken to be 10 years

ΔT_e = Increment of investment (MB)

ΔX_N = Net increment of income per year (MB per year)

Site selection and material and equipment supplies

During the planning of a hydropower plant, the selection of the site and layout of the dam, conveyance structure, power house and transmission and distribution yard are very important and largely depend upon the topographical, geological and hdyraulical conditions. Moreover, in order to save steel, timber, cement etc., full use should be made of available local materials and priority given to local manufacturers in the selection of equipment.

C. Hydrology

China has already established more than 17,000 hdyrological stations of various kinds. Among them, 2,900 are standard stations mainly distributed along big rivers and only 11 per cent are located along small rivers. Since MHG stations are mostly built on small rivers, shortage of hydrological data is a common condition. Generally, the hydrological work of a MHG station is carried out by on-site investigation and by calculations based on data contained in hydrological handbooks. In general, for MHG plants with a unit capacity larger than 500 kW, a hydrological analysis should be presented in the design report; for MHG plants with a unit capacity less than 500 kW, no special hydrological analysis is needed.

The following hydrological data are required for the design of rural MHG stations: run-off data for water energy calculations; flood data for dam design; data on high- and low-water stages for power-house design; flood-stage data for the design of cross structures for conveyance canals.

Run-off calculation

If hydrological data compiled over a period of more than 15 years reflect patterns of change during the high-, medium- and low-water years at the project site, frequency calculations can be directly carried out. If the data cover approximately 10 years, the first step is to extend the series and then calculate the frequency. If the data cover only 6-7 years, it can still be used as a basis for extrapolation. If data have been compiled for only 2-3 years or not at all, the transposition method is recommended. It is then necessary to select a neighbouring basin with a rather long data series and with natural geographical conditions similar to those of the project basin. The long data series can be transposed to the design project. If only precipitation data are available, the run-off can be calculated from precipitation. In that case, when the mean annual average precipitation is approximately 1,500 mm and the mean annual average run-off coefficient over 0.5, there is a good relationship between precipitation and run-off. In an arid region with a high evaporation rate, precipitation and run-off patterns may become irregular.

Hydrological data is usually lacking for medium or small streams. An isohyetal map or statistical data for similar neighbouring regions may be used to determine the frequency characteristics of annual run-off. In general, the coefficient of variation C_v at the centre of gravity of the project basin may be taken from a regional hydrology handbook and the coefficient of skewness C_s dete nined in relation to C_v. Thus, where there is a lack of hydrological data, a mean annual average run-off $\bar{Q}_{aa}$ must be be determined in order to establish the annual run-off frequency curve.

Methods for $\bar{Q}_{aa}$ calculation

Isohyetal method

An isohyetal map is derived from geographical patterns of distribution of hydrological characteristics (annual run-off, coefficient of variation C_v etc.). It is based on the processing and analysis of large amounts of data and drawn up by plotting hydrological values at various stations.

(a) Application of an isohyetal map of the annual average run-off depth ($\bar{y}$) or mean annual average run-off modulus ($\bar{M}$)

Based on the available data and the characteristics of the drainage area, it is possible to establish an isohyetal map of the mean annual average run-off depth $\bar{y}$. If there is no hydrological station near the project site, the mean annual average run-off depth of the project can be determined from the isohyetal map. When the drainage area is small and the isohyets are flat, it is possible to use the $\bar{y}$ at the centre of gravity of the drainage area as the mean annual average run-off depth for the whole drainage basin. Otherwise, the whole basin must be divided into several subareas and its mean annual average run-off depth computed by weighted average of the basin subareas and isohyet.

$$\bar{y} = \frac{\bar{W}_a}{F \times 10^6} \times 10^3 = \frac{\bar{W}_a}{F \times 10^3} \quad (mm) \qquad (5)$$

where F = Basin area in square kilometres

$\bar{W}_a$ = Mean annual average run-off volume in cubic metres

The formula for calculating the mean annual average discharge of the project station is:

$$\bar{Q}_{aa} = \frac{\bar{W}_a}{31.5 \times 10^6} = \frac{10^3 \times \bar{y}F}{31.5 \times 10^6} = \frac{\bar{y}F}{31.5 \times 10^3} \quad (m^3/s) \qquad (6)$$

By means of the isohyetal map for the coefficient of variation C_v of the annual run-off, the C_v at the centre of gravity of the catchment area may be determined and the coefficient of skewness C_s derived by analysis. Using the table of the modulus ratio coefficient K_p of the Pearson type III curve, the K_p value of the specific frequency can be determined. The annual average discharge of the specific frequency may be calculated as:

$$(Q_{aa})_p = \bar{Q}_{aa} \times K_p = K_p \times \frac{\bar{y} \times F}{31.5 \times 10^3} \quad (m^3/s) \qquad (7)$$

In the same way, the annual average discharge of various frequencies can be calculated. Finally, the theoretical frequency curve of the annual average discharge is established.

In China, the isohyetal map of the mean annual average run-off modulus is given in the hydrological handbook of the province concerned. The mean annual average discharge yielded per square kilometer of the catchment area is called the mean annual average run-off modulus $\bar{M}$:

$$\bar{M} = \frac{\bar{Q}_{aa}}{F} \times 10^3 \quad (ls^{-1}km^{-2}) \qquad (8)$$

Hence $\bar{Q}_{aa} = \frac{\bar{M}F}{10^3}$ (m^3/s) (9)

If the isohyetal maps of $\bar{Y}_p$ (annual run-off depth with frequency) and M_p (annual run-off modulus with frequency) are available, it is possible to determine the annual run-off volume of the specific frequency. For example, if the annual run-off of a design percent chance is to be found by means of a $\bar{Y}_p$ or M_p isohyetal map, the annual run-off depth Y_g and annual run-off modulus M_g with specific frequency at the centre of gravity of the catchment area must first be determined. The following formula is then used to calculate the annual average discharge of the design percent chance of the hydropower plant:

$$(Q_{aa})_g = \frac{Y_g F}{31.5 \times 10^3} \ (m^3/s)$$

$$(Q_{aa})_g = \frac{M_g F}{10^3} \ (m^3/s) \quad (10)$$

(b) Method for estimating annual run-off from a precipitation isohyetal map

If there is no run-off isohyetal map, the mean annual average run-off volume of the hydropower plant may be computed on the basis of a precipitation isohyetal map. The formula is:

$$Q_{aa} = \frac{10^3 \alpha \bar{\chi}_a F}{31.5 \times 10^3 \times 10^3} = \frac{\alpha \bar{\chi}_a F}{31.5 \times 10^3} \ (m^3/s) \quad (11)$$

where $\bar{\chi}_a$ = Mean annual average precipitation (mm) derived from the precipitation isohyetal map

α = Run-off coefficient, related to rainfall volume and its intensity, topography of basin, evaporation, soil and water conservation etc. It varies widely, from less than 0.2 to greater than 0.6.

In plain areas with good soil and water conservation and high rates of evaporation and infiltration, a smaller α value is recommended. Since the exact value of the coefficient α is difficult to determine, formula 14 is used for a rough estimate.

Regional hydrological handbooks in China contain isohyetal maps. However, if a drainage area is very small, the influence of non-regional factors increases and the use of an isohyetal map may lead to error.

Estimating annual run-off from annual precipitation

The above-mentioned isohyetal method is relatively simple. However, a hydrological handbook is sometimes difficult to use, or fresh data may have emerged since its publication. In such cases, estimating the annual run-off series by means of the annual precipitation is recommended. This method is rather complex and must be applied carefully to avoid errors.

(a) Evaluating the annual precipitation data for the project basin

For ungauged areas, precipitation data from a nearby rainfall station should be transposed to the design area, bearing in mind the following points:

(a) Data from the closest neighbouring area should be used in transposition;

(b) The rain gauges used for transposition and the project basin should be located in the same climate belt;

(c) The effects of rainfall variation due to elevation must be taken into account, corrections being made if necessary;

(d) Rainfall gauges providing data accumulated over long periods of observation (15-20 years) should be used for transportation.

When only short-term data (covering at least 5 years) is available, it is better first to correlate the short-term data with long-term rainfall data from a nearby gauge in order to extend the term to 15-20 years, and then to transpose it to the project basin.

Correlation analysis has been widely used in hydrological calculation. It can be used for data interpolation and extrapolation, the checking and correction of data, deriving empirical formulas etc.

(b) Evaluating the annual run-off data for the project basin

1. Selecting the reference station and reference basin

Without a hydrological station it is not possible to establish a correlation between annual precipitation and run-off in the project basin. A reference drainage basin and hydrological station must therefore be used to establish a correlation that can be transposed to the project basin. In general, a nearby downstream station with a catchment area adjacent to the project basin is preferable to a reference station and basin.

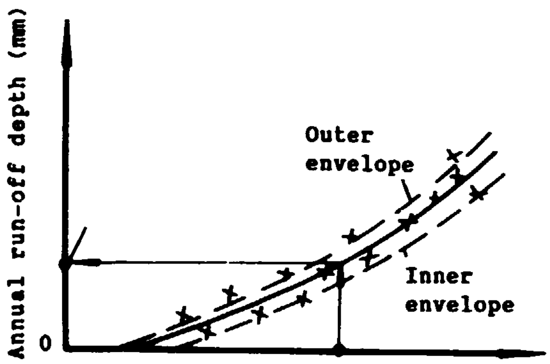
When a reference station has been selected, the correlation points of annual precipitation and run-off of the reference basin should be plotted. If there are several rainfall stations in the reference basin, the average value of precipitation of those stations should be used.

2. Analysis of the correlation curve and transposition for the project basin

During the selection of the reference basin, the factors that will influence the annual run-off of the two basins should be compared and analysed. For a small basin, the following factors are important: average height of the basin; relative direction of slope and air current; forest, farm-land, soil and water conservation; average gradient of basin; forest, soil and geological conditions; and supply of underground run-off.

If conditions in two basins are similar, it is possible to plot a smooth curve through the correlative points and also obtain the inner and outer run-off curve as shown in figure 1.

Figure 1. Precipitation and run-off curve



3. Calculation of the annual run-off curve of the project basin

Evaluating the annual run-off of the project station from annual run-off of the reference station (hydrological analogue method)

If there is a nearby hydrological station where the natural geological conditions are similar to those of the project area, it could be used as the reference station. Long-term hydrological or reference station data are required.

If the difference between the two drainage areas is only 3-5 per cent, the data of the reference station can be directly applied. If the difference is about 10-15 per cent, it can be transposed according to the ratio of area:

$$Q_a = \frac{F}{Fr} Q_{ar} \ (m^3/s) \qquad (12)$$

When the distribution of precipitation is unequal, correction of precipitation must be taken into account.

$$Q_a = \frac{P_a}{P_{ar}} \times \frac{F}{F_r} \times Q_{ar} \ (m^3/s) \qquad (13)$$

where Q_a, Q_{ar} = Annual run-off volume of the project site and of the reference station

F, F_r = Drainage area of the project site and of the reference station (km^2)

X_a, X_{ar} = Annual precipitation of the project site and of the reference station (mm)

Selecting a design sample year

The following three specific years are usually taken as the design sample years:

(a) Low-water year. The run-off of the low-water year is used to predict the performance of the MHG plant in dry years. A frequency of 75-80 per cent is used in the annual run-off series for this sample year;

(b) Medium-water year. Usually a frequency of 50 per cent in the annual run-off series is selected as the basis for a medium-water year;

(c) High-water year. It has a symmetrical relationship to the low-water year. A frequency of 20-25 per cent is used in the annual run-off series for this sample year.

There are two main tasks in the selection of design sample years: to determine, on the one hand, the annual run-off of the design sample year and, on the other, the distribution of the design annual run-off volume.

Design annual run-off volume

According to the above-mentioned methods, the annual run-off volume frequency curve can be plotted first. From this curve, the annual run-off volume of the sample year (of specific frequency) can be evaluated.

Distribution of design annual run-off

The distribution of the stream or river run-off in a year is uneven. The distribution within a year is different not only from other years with different annual run-off volume, but also from years with equal annual flow. Since the flow distribution within a year has a large influence on the operation of the reservoir and hydropower station, a reasonable flow distribution within a year of the design annual run-off is required.

In practice, the selection of flow distribution within a year of the annual run-off involves the determination of a hydrograph of the design annual run-off. For a hydropower station regulated on a yearly basis, the distribution can be shown in the monthly average discharge. For run-of-river hydropower stations or those with daily regulation it is necessary to give the daily discharge of the design year.

(a) Hydrograph of a typical year

The first approach is to select a typical year on the basis of the annual run-off data. The annual run-off volume of the typical year must be equal or close to that of the design year. The flow distribution within the typical year is then used as the distribution of the design year.

The second approach is to select the flow distribution of a year for which the data is adverse and untypical. In this case, an adjustment must be made according to the ratio of the annual run-off volume.

The coefficient of correction K is:

$$K = \frac{\text{Annual run-off of design year}}{\text{Annual run-off of typical year}} \quad (14)$$

The discharge of a typical year times K is the discharge of the design year. The flow distribution within the design year is thus obtained.

(b) Determining the flow hydrograph of an ungauged area

On the basis of data obtained from a similar basin nearby, using one of the two methods described above, the flow distribution within a year of the design annual run-off is determined.

By means of a regional hydrological handbook, the percentage of monthly inflow in relation to the annual run-off volume of the nearby river is computed (this percentage is based on a large body of data). The monthly flow of the problem site is then calculated.

According to the typical annual precipitation distribution within a year of the design frequency (this precipitation is within the catchment area of the project site), the discharge hydrograph of a design year of the same frequency is simulated.

Determining low discharge where hydrological data is unavailable

If there are no hydrological data on the catchment area upstream of the project site, data on the reference basin, where the drainage area, hydrogeological conditions, soil and vegetation are similar to those of the problem basin, may be used to establish estimates. They can be transposed directly or, if necessary, corrected by using the ratio of the drainage areas. Field investigation and measuring are also used to determine the design low daily discharge.

The design per cent chance of an MHG plant has a wide range (50-85 per cent). For a low per cent chance MHG plant with a frequency of 50 per cent or a little higher, field observation works are important. If the required reliability of power supply is high or the water resources are abundant but there are not many consumers, it is suggested that the average daily discharge in the mean dry season be observed and investigated and used as the firm discharge of the MHG plant.

For the selection of low discharge, attention must be paid to the discharge that will be extracted when planning or building a hydraulic project on the upstream reach of the river or tributaries. This discharge must be deducted from the design low discharge.

There are several approaches for investigating and measuring low discharge. They include: estimating the low stage and then calculating the low discharge using the hydraulic formula; measurement by floating marks; measurement by weir; and determining low discharge by means of a daily discharge isohyetal map or table.

For estimating annual run-off in regions where there is a shortage of hydrological data, different approaches may be applied to make a comparison. The run-off estimates may usually be assessed by checking the following points: the balance of the stream flow on the mainstream (including main tributaries); whether precipitation is larger than the run-off volume during the same period, taking into account the run-off coefficient; whether the C_v of the run-off is greater than the C_v of precipitation during the same period; whether the regional distribution of the mean value and C_v is comparable to that of the nearby station; and the regularity of run-off distribution on the flow hydrograph.

Floods

Attention must be paid to flood protection for hydropower stations at the prefectural or county level. If there are flood protection demands downstream, the reservoir must be used for flood detention. When a flood of a certain specific frequency occurs, the downstream discharge may be lowered below the allowable one. This frequency is called the flood protection design standard. Generally, flood protection is 2-20 per cent for agriculture, and 0.2-10 per cent for industrial districts or urban areas.

In a water conservation or MHG project, the main task of flood protection is to guarantee the safety of the hydraulic structures (dam, powerhouse).

Design criteria for medium and small hydraulic structures are presented in tables 11 and 12.

Design discharge of the flood peak

Computation of design peak discharge from flood data

If there are nearby hydrological stations upstream or downstream from the project site, a long-term flood series (over 20 years) is usually available. Frequency analysis can thus be carried out based upon the flood data. Historical flood data are also valuable in determining the design flood discharge. The steps in the calculation are as follows:

(a) Calculate and plot the empirical frequency of the annual maximum discharge series;

(b) Determine the mean of flood peak value $(Q_f)_{av}$, the coefficient of variation $(C_v)_f$ and other statistical parameters;

(c) Take a skewness coefficient $(C_s)_f$, which, for a small catchment, is usually 2-4 times $(C_v)_f$;

(d) Analyse and verify the investigated data on historical floods and estimate their frequency;

(e) Use the principle of curve-fitting to fit the points on the theoretical frequency curve as closely as possible to the points on the empirical frequency curve (the influence of the historical floods could also be taken into account) and eventually obtain the $(C_s)_f$ in times of $(C_v)_f$. The points on the upper part of the curve will be emphasized during the fitting of the curves;

(f) The peak discharge of different frequency can be obtained from the flood frequency curve.

Computation of design peak discharge by other methods

MHG plants are usually located in unguaged regions. In such cases, the synthetic method involving the flood peak, the flood volume modulus of a nearby gauged basin and the storm isohyetal map, as well as the regional synthesis method of storm run-off calculating parameters, is recommended to determine the design flood. An alternative method is to use regional empirical formulas.

If there are reliable historical flood data consistent with the requirements of engineering design, the historical floods can be used to determine the design flood. Various methods of determining design peak discharge are described below.

(a) Estimating design peak discharge from the design storm (rational method)

When the drainage area of the river is smaller than 500 km^2 in a mountainous or semi-mountainous region, the basic formula for estimating flood peak discharge Q_f from the intensity of storms is as follows:

$$Q_f = 0.278\,\psi i_p F = 0.278\,\psi \frac{S}{\tau^n} F \ (m^3/s) \qquad (15)$$

where 0.278 = Coefficient of unit exchange

i_p = Design storm intensity (mm/h)

ψ = Coefficient of peak run-off (ratio of the run-off volume to the storm volume during the flood peak period)

S = Rainfall density (maximum one-hour precipitation) (mm/h)

τ = Time concentration of flow (or time of flood collection) (hours). In a small basin, it may be assumed that the time concentration of the peak discharge equals the duration of the storm.

n = Storm recesssion coefficient

F = Drainage area (km^2)

The main parameters and coefficients of the rational method are presented below.

F = Drainage area of the control section of the project site

L = Distance from the remotest point of the watershed to the project site along the river channel (km)

J = Average gradient of the river channel

The above-mentioned three parameters may be measured from the 1:50,000 topographical map.

Storm parameter S (rainfall density) may be formulated as follows:

$$S = \frac{H_{24p}}{24^{1-n}} = \frac{K_p H_{24}}{24^{1-n}} \text{ (mm/h)} \tag{16}$$

where H_{24p} = 24-hour design storm volume in a given frequency (mm)

H_{24} = Mean annual maximum 24-hour storm volume (mm) (usually obtainable from isohyetal storm parameter maps)

n = Storm recession coefficient (which varies with rainfall duration). When the duration of the rainfall is less than one hour, take $n = n_1$; if the duration is one hour or longer, take $n = n_2$ (n may be obtained from a hydrological handbook).

K_p = Can be obtained from the K_p table (based on local data or = the formula $C_{s24} = 3.5\ C_{v24}$) by means of frequency p and C_v, C_s of the maximum 24-hour storm

Time concentration τ (hours) is the duration of the flood concentration in the basin. It is related to the length of the river, channel gradient and velocity of flow concentration. It also varies with the size of the flood. There are empirical formulas and nomographs of time concentration which are adaptable to local conditions.

The flood peak run-off coefficient ϕ is related to topographical conditions, water and soil conservation, flood frequency and its antecedent factors. If those factors are similar, the smaller the drainage area, the larger the ϕ value will be.

(b) Empirical formula

On the basis of the available flood data, and taking into account natural geographical factors, empirical formulas for determining flood peak discharge can be applied in the various regions. One of the formulas is as follows:

$$(Q_f)_p = C_p F^K \text{ (m}^3\text{/s)} \tag{17}$$

where $(Q_f)_p$ = Peak discharge of a certain frequency (m^3/sec)

F = Drainage area (km^2)

C_p = Flood peak discharge modulus. Its empirical parameter, which is concerned with frequency, is presented in the regional hydrological handbook. Usually, for a fan-shaped basin with a steep channel gradient, the value of C_p becomes larger; while for a narrow-shaped basin with a flat channel gradient, the value of C_p becomes smaller.

K = Area coefficient, which is an empirical coefficient related to natural geographical factors (also presented in the hydrological handbook).

Another form of the empirical formula is:

$$(Q_f)_p = qSF^{2/3} \ (m^3/sec) \qquad (18)$$

where S = Rainfall density (mm/h) (presented in the regional hydrological handbook or calculated by means of formula (16))

q = Peak discharge parameter, as shown in table 13

Table 13. Calculation of peak discharge parameter

Area of flood concentration	River channel gradient (J) (percentage)	Run-off co-efficient (φ)	Velocity during concentration (v) (m/s)	Peak discharge parameter (q) a/
Rocky mountainous region	>15	0.80	2.2-2.0	0.60-0.55
Hilly region	> 5	0.75	2.0-1.5	0.50-0.40
Loess hilly region	> 5	0.70	2.0-1.5	0.47-0.37
Plain, flat sloping region	> 1	0.65	1.5-1.0	0.40-0.30

a/ q is calculated by formula $q = 0.42 \ \phi v^{0.7}$.

(c) Investigation and calculation of historical flooding

The main point for the investigation of historical flooding is to discover reliable flood traces. From these, the corresponding peak discharge can be calculated. Generally, according to the surveyed longitudinal section and cross-section of the river bed and the flood surface curve, the hydraulic factors of the design section can be calculated. The flood peak discharge corresponding to the investigated flood stage can then be calculated using the hydraulic formula.

Design flood volume

For medium or small projects, the daily storm flood volume is generally used or, at times, a three-day flood volume. Flood volume observation of one to three days, involving frequent analysis and calculation, is carried out for gauged rivers.

In medium or small drainage areas where there is a shortage of data, one flood is usually analysed. Two methods of estimation are used. One involves estimating the volume of one flood from the approximate accumulated volume after a storm lasting a maximum of 24 hours.

$\bar{W}_{df}$ (design flood volume) = 1,000 $(h_{24})_d$ F m^3 (19)

where $(h_{24})_d$ = Maximum 24-hour excess rainfall depth (mm) of design flood frequency

The steps for calculating $(h_{24})_d$ are as follows:

(a) Obtain from a hydrological handbook the mean annual average for a maximum 24-hour storm volume $\bar{H}_{24}$ and $(C_v)_{24}$ of the annual maximum 24-hour storm;

(b) Find out the design storm modulus factor $(K_p)_d$ from the hydrological handbook, according to its design flood frequency and $(C_v)_{24}$;

(c) Calculate the 24-hour design storm volume $(H_{24})_d$ from $\bar{H}_{24}$ and $(K_p)_d$ formulated in $(H_{24})_d = (K_p)_d \, \bar{H}_{24}$; (20)

(d) On the basis of $(H_{24})_d$ and the H_{24}-H_{24} curve presented in the hydrological handbook, obtain the maximum 24-hour excess rainfall depth $(h_{24})_d$.

The other method involves estimating flood volume by 24-hour design storm volume and the corresponding run-off coefficient.

$\bar{W}_{df}$ = 1,000 $(H_{24})_d$ · [illegible] · [illegible]$_{24}$ · F (m^3) (21)

where $(H_{24})_d$ = 24-hour design storm volume (mm) (obtainable from the hydrological handbook)

[illegible] = Storm point - area ratio (obtainable from the hydrological handbook). The small catchment value is larger when F < 300 km^2 and [illegible] approaches 1.

[illegible]$_{24}$ = Run-off coefficient of a 24-hour storm (obtainable from the hydrological handbook)

Design flood hydrograph

The two methods described below are used to calculate the hydrograph for flood routing.

Enlarging the typical flood hydrograph. If the annual maximum flood series is available, the design flood hydrograph can be derived by enlarging the typical flood hydrograph. High-water years for which data are both representative and reliable, and when the flood peaks are adverse to engineering safety, should be selected.

The discharge on the design flood hydrograph is the product of the discharge on the typical flood hydrograph and a coefficient $K_f > 1$ (i.e. enlarged).

$$K_f = \frac{Q_{df}}{Q_{tf}} \quad (22)$$

where Q_{df} = Design flood peak (m^3/s)

Q_{tf} = Flood peak on the typical flood hydrograph (m^3/s)

Simplified design flood hydrograph. The establishment of the design flood hydrograph in the unguaged watershed is related to the method used to compute the flood peak discharge. The flood hydrograph can be directly derived from both the unit hydrograph and isochrones. If the flood peak is calculated by means of formulas, only the peak discharge value will be obtained, but no flood hydrograph. The simplified design flood hydrograph must therefore be applied.

Mountain tributaries have small catchment areas, the basin slope and channel gradient are rather steep, and the flood rises and falls fiercely. Here, the design flood hydrograph for small projects can be simplified as a triangle, as shown in figure 2. Preferably, the simplified hydrograph should be selected with reference to the natural flood hydrograph data of nearby regions.

The peak volume relation of the simplified triangle of the design flood hydrograph is as follows:

$$\bar{W}_{df} = 1/2\ Q_{df} \cdot T$$

$$T = \frac{2\bar{W}_{df}}{Q_{df}} \qquad (23)$$

where $\bar{W}_{df}$ = design flood volume

Q_{df} = design flood peak

An analysis of the available data makes it possible to establish an empirical relation between the duration of rising segment T_i, flood duration T and various catchment areas.

The relationship between $\frac{T_i}{T}$ and catchments in a district in China is shown in table 14. It is the result of the analysis and synthesis of T_i and T of many flood hydrographs.

By means of formula 23, T can be obtained if the design flood peak discharge and design flood volume are given. The T_i can also be determined by reference to the $\frac{T_i}{T}$ - F of the problem basin or a nearby similar basin.

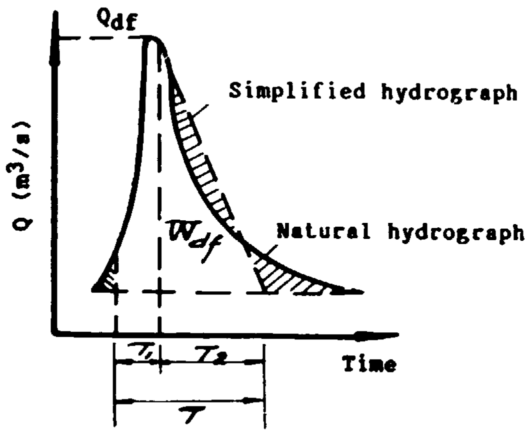
Tables 14. Relationship between T_i/T and catchment area

Catchment area F (km^2)	T_i/T
1-3	0.374
4-10	0.352
11-20	0.337
21-40	0.325
41-100	0.312
101-200	0.300
201-500	0.289
501-1 000	0.277

Note: T_i is the duration of the flood rise and T the flood duration.

A simplified triangular design flood hydrograph can then be plotted, as in figure 2.

Figure 2. Simplified triangular flood hydrograph



Establishment of a stage-discharge relation

For the ungauged watershed, the stage-discharge relation can be derived from the results of hydraulic calculations based on the available data. The selection of roughness must be carefully done. The configuration of the river-bed and variations in control conditions must be considered in advance.

If there are stage data but no discharge data, the upstream or downstream stage-discharge curve may be transposed to the problem site by determining the correlation between the upstream and downstream stages. Extrapolation is necessary if design conditions lie outside the available data range. The possible influence of back-water should also be considered.

D. Water energy

Water energy design is used to determine the power features of the hydropower plant. It involves flow regulation, firm power, installed capacity and mean annual power output etc. These indexes reflect the potential benefits of the hydropower plant and the extent of utilization of the water resources. The selection of the installed capacity of a run-of-river and daily regulated MHG plant will be dealt with in this section.

The following technical data are collected for water energy design:

(a) Hydrological data, including characteristics of the drainage basin, flow series and stage-discharge curve at the plant site, and monthly precipitation and evaporation data;

(b) Reservoir area and capacity curves;

(c) Demands of multiple-purpose utilization, including water demand for irrigation, navigation and log transportation;

(d) Load status, including the range of the power supply for the project plant and the load characteristics of the regional grid.

For the water energy design of rural MHG plants, both the data required and the calculations can be simplified.

Electrical load

In rural China, electricity is mainly used for irrigation and drainage, the processing of agricultural products, field operations, repairing farm machinery, animal husbandry, the manufacture of tiles and paper, sugar production etc. Average power consumption for the different uses is shown in table 15.

Table 15. Average energy consumption in rural China

Activity or industry	Energy consumption
	Kilowatt-hours per tonne
Edible oils	60-90
Fertilizer	30
Grinding	40
Husking	30
Mining	8
Paper	500-600
Pesticides	80
Sugar	12
Threshing	6-12

continued

Table 15 (continued)

Activity or industry	Energy consumption
	kWh per 1,000 MB
Bricks and tiles	50
Farm machinery	40-80
	kWh per m3
Electrical pumping	
Head = 20 m	0.091
Head = 40 m	0.181

Note: Electricity is supplied for illumination at the rate of 15-25 W per household.

Power requirements in the near and distant future must be estimated in order to determine the appropriate plant size. If plant capacity exceeds the demand load, a waste of capital occurs. Conversely, if the demand load exceeds plant capacity (when the water head and flow are fully utilized), either a new plant will have to be constructed or the existing one enlarged. For the independently operated run-of-river station, only maximum demand load is calculated. The following data are required: range of power supply, scale and type of production, number of shifts, load period, capacity and rate of utilization of equipment; annual and monthly power consumption; present and expected future population of towns located within the range of power supply and their power consumption, including agro-based subsidiary lines.

The range of power supply of a hydropower plant will be determined by the regional load and its possibilities of development. The relationship between the range, transmission voltage and transmission capacity is shown in table 16.

Table 16. Analysis of transmission data

Voltage of transmission line (kV)	Capacity of power transmission (kW)	Transmitting distance (km)
0.22	<50	0.15
0.38	<100	0.6
10	200-2 000	6-20
35	1 000-10 000	20-70

The annual load for industrial purposes is fairly even, but the daily load varies widely according to different working shifts and the kind of production. In China at present, electrical pumping and drainage account for the largest consumption of hydropower in rural areas. Agricultural electricity requirements are subject to seasonal variations. The load must be abruptly increased for pumping and drainage and a day and night power supply is required for irrigation. The power supply for sideline occupations in rural areas is mostly concentrated in winter.

The illumination load in towns and rural areas varies within a 24-hour period and over a year.

Daily load

The sum of industrial, agricultural and lighting loads provides the typical daily load on the power supply, as illustrated in figure 3.

There are three characteristic values (P_{max}, P_{av} and P_{min}) in the daily load diagram. P_{max} indicates the maximum load in a day. In order to meet the demand for power supply, the total installation capacity of the hydropower plants must exceed P_{max}. P_{av} is the average load in a day: 24 x P_{av} is the daily power supply. P_{min} is called the base load. Using these three characteristic values, the daily load diagram can be divided into three parts. Peak load (the load with large fluctuations) is above the P_{av} part. The middle load is between the peak and base load.

Annual load diagram

The annual load diagram is used to express the load variations within a year, usually taking the load as the ordinate and time (month or day) as the abscissa.

If the agricultural power supply is large, the peak load will not occur during the dry season. For example, if a hydropower plant is designed mainly to supply power for pumping and drainage, there will be no load demand during the dry season. It is therefore not important to determine the probability of discharge during the dry season, but it is essential to study the hydrological characteristics during the drainage season to determine the firm power and maximum working capacity of the hydropower plant.

Two typical daily load diagrams for both winter and summer are usually provided according to the year of the design load level. With regard to rural MHG, it is not necessary to set out the load diagram, since only the load characteristics of the power supply will be taken into account.

<u>Run-of-river hydropower plant</u>

Determination of firm power

When hydrological data is available, the duration curve of the daily average discharge should first be plotted. According to the design of the hydropower plant, the firm discharge Q_G on this duration curve should be determined.

When hydrological data are not available, the method described in section C of this chapter should be used to determine the firm discharge corresponding to the design percent chance.

The firm power of the hydropower plant is formulated as follows:

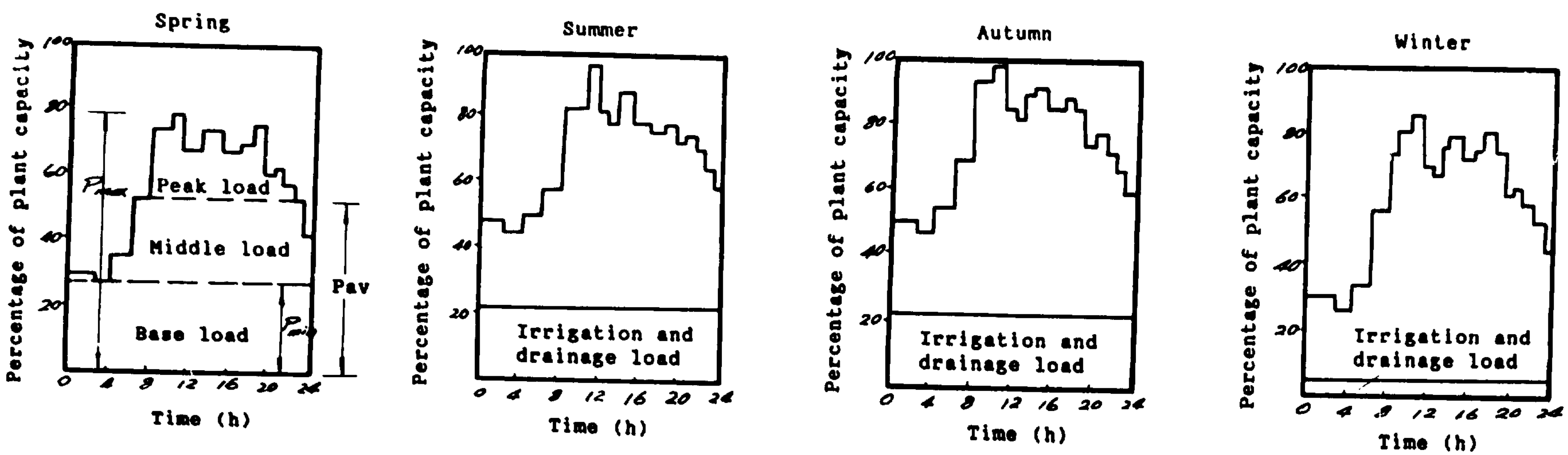
$$N_G = AQ_GH \quad \text{(kW)} \qquad (24)$$

where N_G = Firm power

Q_G = Firm discharge

A = Coefficient of firm power

Figure 3. Typical daily load diagrams



Mean annual energy output

Owing to the variation of power output in different hydrological years, the mean annual power output is adopted as an index to express the yield of a hydropower plant.

Figure 4. Daily average output duration curve

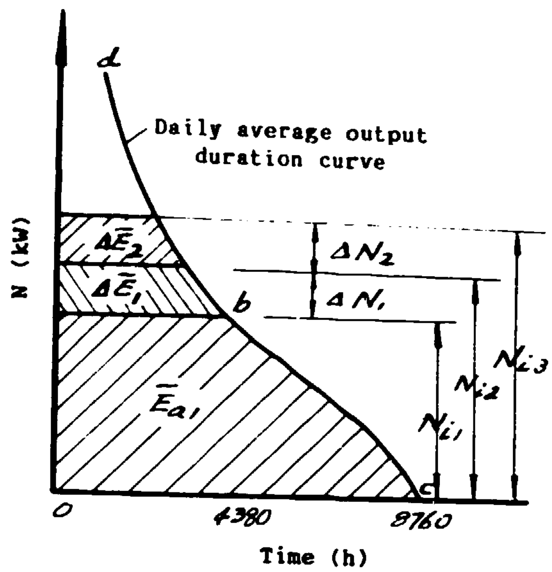


Figure 4 shows the duration curve of the daily output in an average year, taking N_{i1} as the installed capacity of the plant. N_i and the duration curve intersect at point b. In figure 4 the bd segment of the curve indicates that the natural flow output is larger than N_i. However, the output of the plant is limited by N_i. If the bc segment of the curve indicates that the natural flow output is less than N_{i1}, then the plant is operated according to bc. The Oabc area represents average annual electricity output ($\bar{E}_{a1}$ in figure 4). The mean annual output varies with the installed capacity of the plant. When the installed capacity is increased from N_{i1} to N_{i2} ($N_{i2} = N_{i1} + \Delta N_1$), the annual energy output is increased from $\bar{E}_{a1}$ to $\bar{E}_{a1} + \Delta\bar{E}_1$. In a normal case, the $\bar{E}$ decreases as installed capacity increases; i.e., if $\Delta N_1 = \Delta N_2$, $\Delta\bar{E}_2 < \Delta\bar{E}_1$. Several alternatives are proposed with different installed capacity to calculate the mean annual output and then to plot the $N_i - \bar{E}_a$ curve. The designed mean annual output will be checked from this curve when the installed capacity of the hydropower plant has been selected.

Determining the installed capacity

The capacity of a run-of-river hydropower plant is composed of the maximum working capacity, spare capacity and seasonal capacity.

The maximum working capacity is installed to meet the maximum load requirements of the consumers. The maximum working capacity will usually not exceed the firm power.

$$N_W = N_G \text{ (kW)} \tag{25}$$

where N_W = Maximum working capacity

N_G = Firm power

There is no spare storage capacity in the run-of-river hydropower plant. It has no ability to undertake the emergency spare or load spare capacity in the grid.

Repair work on units in a hydropower plant can be done in the dry season or low load period. If irrigation is the main function of a hydropower plant, repairs can be planned for the non-irrigation period. If there are still difficulties, additional spare capacity for repairs must be considered.

The maximum working capacity of a run-of-river hydropower plant is determined according to the firm discharge. In order fully to utilize the water energy in the high-water season, some seasonal capacity may be installed when the following conditions are met:

(a) There is a thermal power plant in the grid so that the seasonal power output in the high-water period can save the fuel of the thermal power plant;

(b) There are seasonal power consumers within the range of the power supply. If there are large consumers such as electrical furnaces for iron or the production of aluminium and fertilizers, the benefit of seasonal energy may be fully utilized;

(c) The plant is integrated into the big grid. Seasonal power can then be transmitted to the big grid;

(d) There is an annual regulating reservoir in the grid. During the generation of seasonal power by the run-of-river hydropower plant, the plant with an annual regulating reservoir will impound the water in the reservoir. This means that the water and the power are mutually compensated for.

Seasonal capacity may be determined in three ways.

<u>Annual operating hours for additional capacity</u>. The utilization of seasonal capacity will increase the capital cost, overhead expenses etc. of the hydropower plant. The rate of increase of seasonal output will be reduced when installation costs are high. Generally, h_c is used as a reference index to verify the viability of the increment for seasonal capacity.

$$h_c = \frac{\Delta E}{\Delta N} \geq h_s \text{ (hours)} \tag{26}$$

where ΔN = Increment of installed capacity (kW)

ΔE = Increment of annual power output corresponding to ΔN

h_c = Annual operating hours of the additional capacity according to the duration curve of the natural flow daily output (hours)

h_s = Adopted annual operating hours of the additional capacity specified by the relevant department

Return years of the increment investment. The viability of seasonal capacity in terms of the annual benefit of seasonal power is determined. It is reasonable if the return is within 3-5 years.

Annual operating hours for seasonal capacity. This is shown by the following formula:

$$h_c = \frac{\bar{E}_s}{N_s} \geq h_s \text{ (hours)} \qquad (27)$$

where $\bar{E}_s$ = Seasonal energy

N_s = Seasonal installed capacity

h_c = Computed annual operating hours of seasonal capacity

h_s = Specified value of the annual operating hours for seasonal capacity, which is related to the regional energy and economic conditions, and especially to the consumption of seasonal energy. In some regions in China, 1,800-2,500 hours are recommended (2.5-3 months).

For rural MHG or hydropower plants with a rather large capacity but with deficient economic and load data, various simplified methods are proposed for selecting the installed capacity.

Installed capacity as a multiple of the firm power

The firm power of the hydropower plant is first calculated and then an analysis is made of the composition of the grid, load characteristics, water resources and multi-purpose utilization to determine the installed capacity as a multiple of the firm power.

$$N_i = CN_G \qquad (28)$$

where C = Ratio of N_i to N_G

N_i = Installed capacity

N_G = Firm power

The value of C for hydropower plants operating under varying conditions in several regions is given in table 17.

Table 17. Ratio of installed capacity to firm power for selected hydropower plants

Operating conditions of plant	Ratio of installed capacity to firm power
Rural MHG (< 500 kW) plant operating independently	1.5-3.5
With high percentage of hydropower in the grid and with regulating storage in the plant	
Power generation only	2.0-3.5
Mainly power generation and secondarily for irrigation	2.5-4.0
Mainly for irrigation	
Ordinary facilities	3.0-5.0
Good facilities	2.5-4.0
With low percentage of hydropower in the grid	
Power generation only	2.5-4.5
Mainly power generation and secondarily for irrigation	3.0-4.5
Mainly for irrigation	
Ordinary facilities	3.5-5.5
Good facilities	3.0-4.5

Installed capacity based on annual hours of utilization

The mean annual power output E_a divided by the total installed capacity N_i of the plant gives the annual utilization hours h_a of the plant, represented by the following formula:

$$h_a = \frac{E_a}{N_i} \qquad (29)$$

h_a is equivalent to the annual operation hours under full load and indicates the extent of utilization of mechanical and electrical equipment.

The designed number of annual utilization hours in some regions is shown in table 18.

Table 18. Design annual utilization hours of installed capacity

Type of demand and operating conditions	Design annual utilization hours according to system of regulation		
	Run-of-river	Daily storage	Yearly storage
Rural hydropower plant (<500 kW)			
Agricultural and sideline production and illumination	>4 500	>3 500	
Small industry and town illumination	>4 500	>3 500	
Rural hydropower plant (<500 kW)			
Agricultural and sideline production and illumination	4 500	3 500	
Small industry and town illumination	4 500	3 500	
Mainly for pumping and secondarily for other uses	About 5 000	About 4 500	2 500-4 000
With high percentage of hydropower in the grid			
Rather large industrial users in continuous production	5 000-6 000	5 000-6 000	4 000-5 000
Ordinary consumers	5 000-6 000	4 000-5 000	3 500-4 000
With low percentage of hydropower in the grid	4 500-5 500	3 500-4 500	3 000-4 000

The choice of a method for selecting the installed capacity will depend upon concrete conditions. When tables 16 and 17 are used, the following points must be taken into account:

(a) In regions rich in water resources, a high value of design annual utilization hours (h_a) and a low ratio between installed capacity and firm power (C) will be selected;

(b) In the continental climate area where the flow distribution of creeks and rivers is uneven within a year, C may be used as the high value and h_a as the low one;

(c) If there are several hydropower plants (with large regulating storage) in the grid, the new plant will undertake a rather uniform load. A high h_a value and a low C value are therefore proposed, and vice versa;

(d) In the grid, when there is large variation in the daily load diagram, if the base load and partial middle load are undertaken by the thermal plant and run-off hydropower plant, the low h_a and high C value will be selected for the new plant, and vice versa;

(e) In hydropower plants which utilize the irrigation water (regulated by reservoir) as its water source, the firm power of this type of plant will be rather low and the seasonal energy rather high. In this case, the high C value will be taken;

(f) The h_a and C of the non-regulating hydropower plant depend upon the extent of utilization of seasonal energy. If there is spare capacity in the plant, low h_a and high C value are recommended.

Installed capacity based on the standardized turbine-generator unit

No matter which method is adopted to determine the installed capacity, manufacture and supply of the mechanical and electrical equipment must be taken into account. In some cases, the installation of a hydropower plant is mainly determined by the availability of the units. If a standardized turbine generator unit is selected, purchase is easy.

With regard to the number of units in a hydropower plant, when $N_i <$ 1,000 kW, two units are usually preferable; when N_i = 1,000-3,000 kW, 2-3 units are selected. The number of units in most MHG plants is less than four.

The capacity of each unit is usually equal or near to the firm power. If no suitable unit can be offered, the capacity of each unit should be at least 1.6 times the firm power.

In sum, there are three simplified approaches for determining the installed capacity of a hydropower plant. The first approach is to take firm power as a prime factor. After calculating the maximum working capacity, selection of the installed capacity is worked out by analysis or is a multiple of the firm power. The second method involves determining the annual utilization hours, which are related to the regional power resources and the regulating ability of the plant. The third approach is based on the standardized turbine-generator units. In the practical design work, for rural MHG plants (installed capacity less than 500 kW) the water energy design will be kept as simple as possible to avoid complex calculations.

Daily regulating hydropower plant

The daily regulating hydropower plant provides regulating storage with the capacity to redistribute the natural flow within one day. The calculation of the firm power and mean annual power output of the daily regulating hydropower plant is basically the same as with a run-of-river plant. They differ in that the upstream normal high-water level of the run-of-river plant is a constant, while the upstream water level of the daily regulating plant fluctuates between the normal high-water level and the dead water level. The average water level is used to calculate the power.

With regard to the installed capacity of daily regulating MHG plants, the 24-hour power production is equal to the energy produced by the natural inflow of the same _ y, since the plant is able to redistribute the natural flow within one day. The maximum load may therefore be larger than the daily average output and the installed maximum working capacity (to meet the maximum load demands) larger than the natural flow of firm power.

The two cases described below are of particular interest.

Concentrated power generation

Figure 5 is based on a daily regulating hydropower plant. The design low-water natural inflow is concentrated in h hours for power generation. The maximum discharge is:

$$Q_{max} = \frac{Q_G \times 24 \times 3{,}600}{h \times 3{,}600} = \frac{24}{h} \cdot Q_G \tag{30}$$

Hence, the maximum working capacity of the daily regulating hydropower plant is:

$$N_W = AQ_{max} H = A \cdot \frac{24}{h} Q_G H \tag{31}$$

$$= \frac{24}{h} N_G (kW)$$

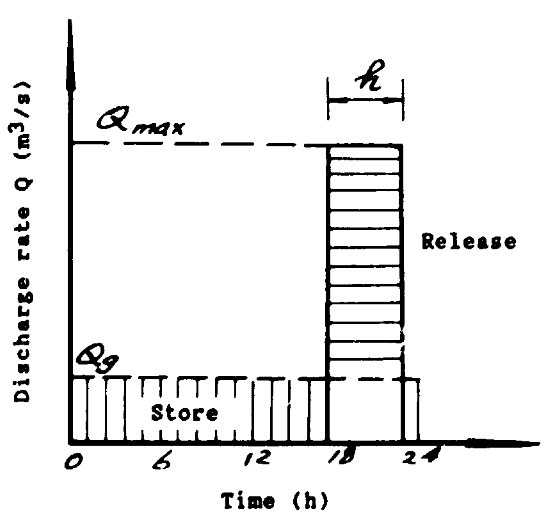
where N_W = Maximum working capacity

N_G = Firm power

A = Coefficient of firm power

With the same design characteristics, the maximum working capacity of the daily regulating hydropower plant is $\frac{24}{h}$ times that of the non-regulating plant.

Figure 5. Daily regulation for concentrated power generation



The vertical shadowed area in figure 5 is the required daily regulation storage. The formula is:

$$\bar{V}_d = (1.10\text{-}1.15) \times Q_G(24-h) \times 3{,}600 \ (m^3) \qquad (32)$$

where 1.10-1.15 = Safety coefficient, taking into account insufficient and incorrect data, as well as computation error.

Interval power operation

In considering the demand of both electricity and water consumers, the water and power supply is divided into several times intervals according to the natural inflow. The first step is to determine the water and power supply of the time intervals other than the peak load period and to deduct them from the daily inflow volume. The remaining water is used for the peak load period. Therefore,

$$Q_{max} = \frac{Q_G \times 24 \times 3{,}600 - (\bar{V}_1 + \bar{V}_2)}{h \times 3{,}600} \ (m^3/s) \qquad (33)$$

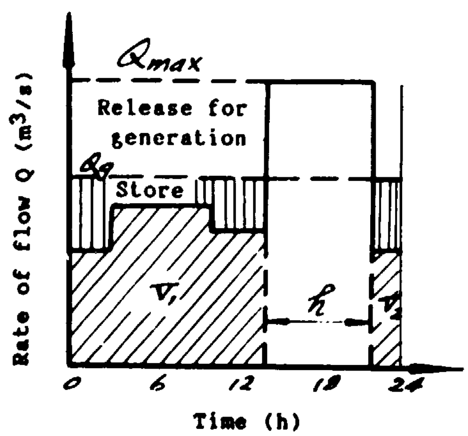
The maximum working capacity

$$N_W = A \cdot Q_{max} \cdot H = A \left[\frac{Q_G \times 24 \times 3{,}600 - (\bar{V}_1 + \bar{V}_2)}{h \times 3{,}600}\right] \times H \qquad (34)$$

where H = Head difference between the average upstream water level and the downstream water level (varies with the corresponding discharge)

The required daily regulation storage is shown in the shadowed area of figure 6.

Figure 6. Daily regulation for interval power operation



With regard to spare capacity and seasonal capacity, there is no substantial difference between the run-of-river plant and the daily regulating plant. The only difference is that if there is a daily regulated hydropower plant with rather large capacity, short distance to the load centre and short water conduit, the plant could be considered for undertaking the extra load for frequency modulation.

When a major hydropower plant at the prefectural or county level is planned, it is better to work out the design daily load curve of the grid, and then, by means of the daily energy mass curve, to determine the maximum working capacity of the plant. The first step is to calculate the daily firm output $E_G(E_G = 24\ N_G)$ according to the firm power N_G. The second step is to consider the load of the grid and the characteristics of the main power stations of the grid, and then to decide the working position (the load to be taken by the plant). Finally, from the balance of daily firm output on the daily load curve, the maximum working capacity would be determined.

<u>Annual regulating hydropower plant</u>

Annual regulating storage must be provided for an annual regulating hydropower plant. The natural inflow will be reallocated within the year in order to meet demand for power and other purposes.

Flow regulation is based on the water balance at any time interval. The difference between outflow and inflow is the variation of storage during that interval. It is shown in the following formula:

$$\Delta\bar{W}_N - \Delta\bar{W}_c - \Delta W = \pm\Delta\bar{W}\ (m^3) \qquad (35)$$

where $\Delta\bar{W}_N$ = Natural inflow into the reservoir during certain time intervals (m^3)

$\Delta\bar{W}_c$ = Outflow of the reservoir during the same period for water supply to the relevant department (m^3) (including waste water in the flood season)

$\Delta\bar{W}$ = Water losses in the reservoir during the same period (m^3)

$\pm\Delta\bar{W}$ = Variation of storage during the same period

Since both the natural inflow and water consumption are given, it is easy to find out the starting and ending time of the water supply and thus to determine the dry water season. The water balance formula is used to perform calculations in time intervals and measure the water deficiency. The total water deficiency during the dry season is the total volume of water which will be supplied by the reservoir, that is, the required volume of storage regulation.

E. Types of MHG plant

The capacity of hydropower generation is proportional to the water head and flow. In order to obtain hydropower, the head difference between the upstream and downstream of the hydropower plant must be determined.

According to the form of head concentration, hydropower plants are classified into three types.

Dam-type plant

The construction of a dam or movable barrage impounds the flow of the river, forms a reservoir and raises the upstream water level. There is therefore a head difference between the upstream reservoir level and the downstream river level. In a dam-type hydropower plant, the reservoir water is diverted to the plant by means of a tunnel or pipe and water turbine generator units generate the power. However, according to the layout of the hydropower-houses, the plants can be subclassified into two types; hydropower-houses acting as water-retaining structures and hydropower-houses located at the downstream side of the dam.

Hydropower-houses acting as water-retaining structures

Figures 7 and 8 show the Ganqi MHG plant, Hunan Province, a hydropower plant erected in the river bed. The stability of the structure is maintained by the combined weight of both the dam and the power-house. The drainage area is 1,170 km^2, which is 96 per cent of the Mi river basin. It is a multi-purpose water conservation project for irrigation, power generation and navigation. The maximum height of the dam is 20.5 m and the length of the dam axis is 454 m. The hydraulic structure is composed of a pumping station, a hydropower station, a navigation lock, log passers and the dam. Ten water turbine generator sets were installed in the power-house with a total capacity of 12,500 kW. The design head is 10.5 m and design discharge 160 m^3/s. Mean annual output is 76.8 million kWh. This MHG plant was integrated into the southern Hunan grid.

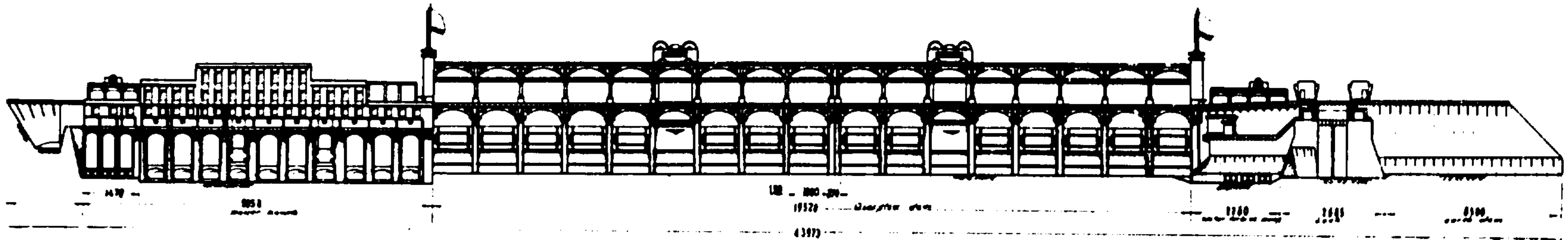
Hydropower-houses located at the downstream side of the dam

Figures 9, 10 and 11 show the Yanwotan hydropower plant, Hunan Province. The power-house is located on the right bank of the downstream river bend. The water is diverted to the power-house by a tunnel 3.5 m in diameter. The drainage area of the dam site is 457 km^2. The mean annual run-off volume is 407 million m^3 and the storage capacity is 87.6 million m^3 at the normal high-water level. The reservoir thus has the capacity for yearly regulation.

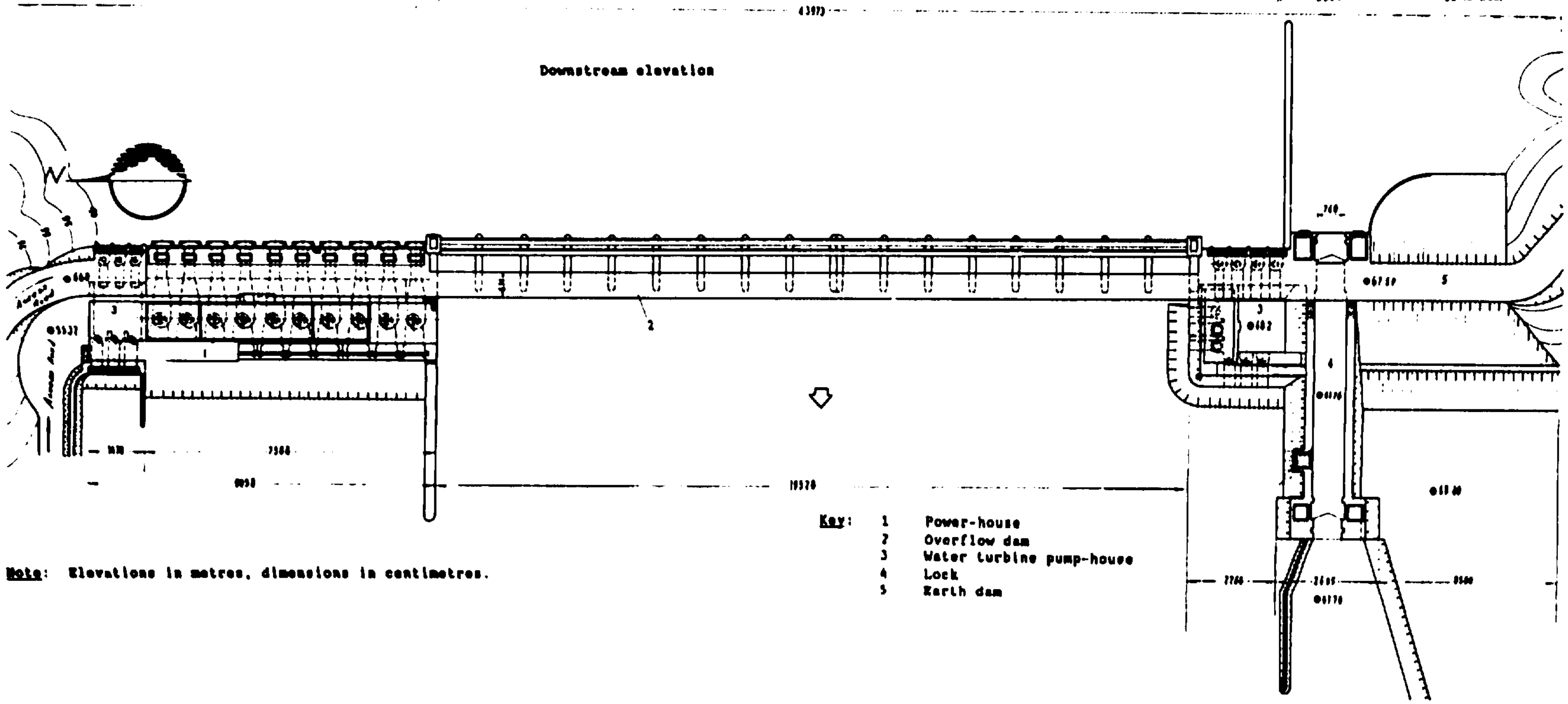
The project involves an overflow masonry hollow gravity dam, power-house and tunnel. The crest length along the dam axis is 140 m and the maximum dam height is 66 m. There are two water turbine generator units with a capacity of 3,000 kW each and another unit installed in the power-house, the total installed capacity being 9,200 kW. The design flow of the turbines are 12 and 12.6 m^3/s, and the maximum working head is 50 m. The annual output of the plant is 33.9 million kWh. In order to ensure full utilization of seasonal power, the plant was put into parallel operation with a 3,750 kW county-run small thermal plant. During the high-water season, the hydropower plant plays the main role, while in the low-water period, the thermal plant is used to supplement the power supply. The Yanwotan hydropower plant supplies both power to the county proper and reactive power to the Central Hunan grid.

Figures 12 and 13 show the Mei stream stage I hydropower plant. The height of the earth dam is 47 m with a storage capacity of 65.5 million m^3. The installed capacity of the plant is 5,000 kW. The plant was put into commission in 1962 and completed in 1967. The tailrace of the stage I plant can be used for the irrigation of farm-land and as the water source for the downstream cascade power plants.

Figure 7. Ganzi MHG station (1)



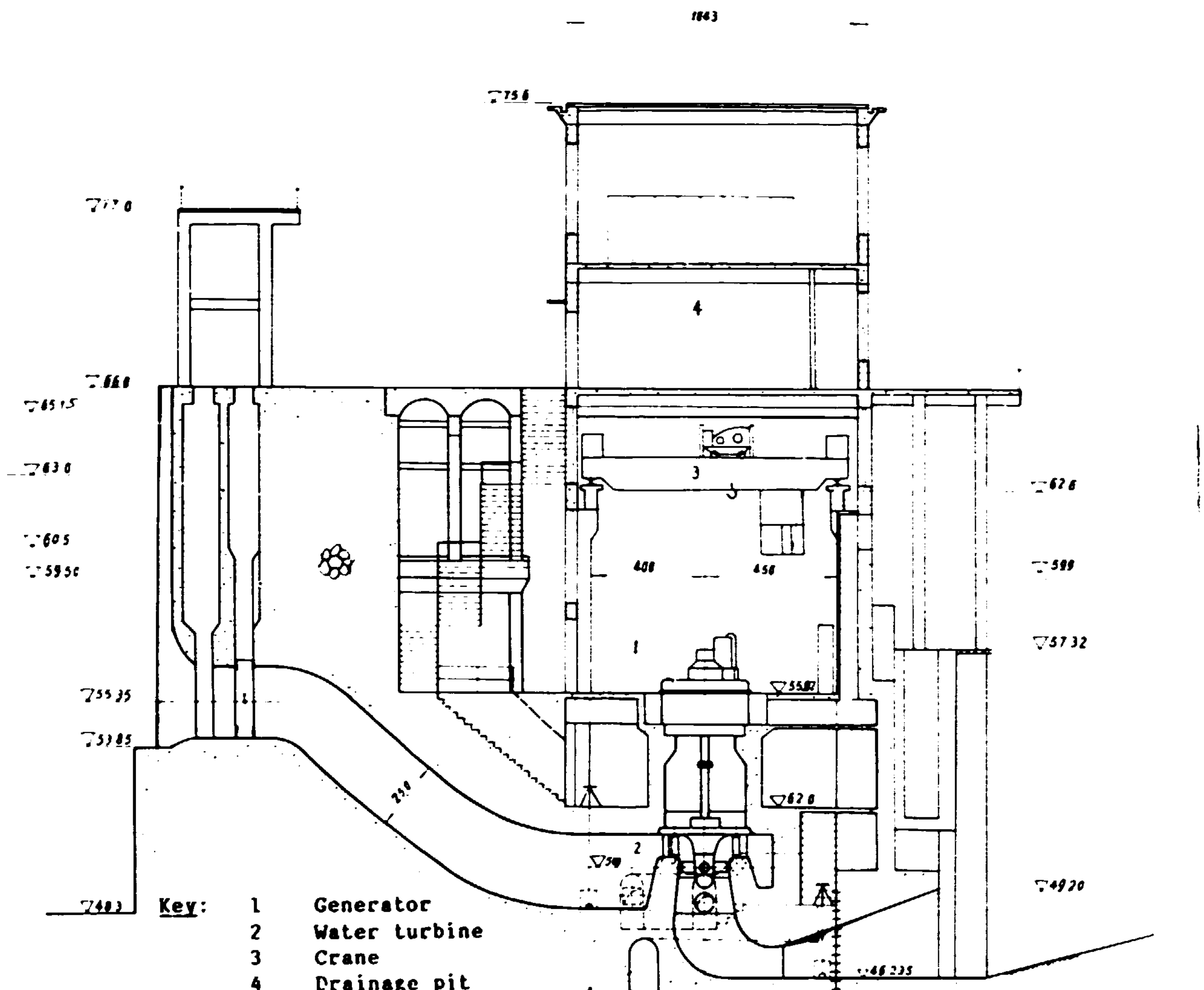
Downstream elevation



Key:
1 Power-house
2 Overflow dam
3 Water turbine pump-house
4 Lock
5 Earth dam

__Note__: Elevations in metres, dimensions in centimetres.

Figure 8. Ganxi MHG station (2)



Note: Elevations in metres, dimensions in centimetres.

Figure 9. Yanwotan MHG station

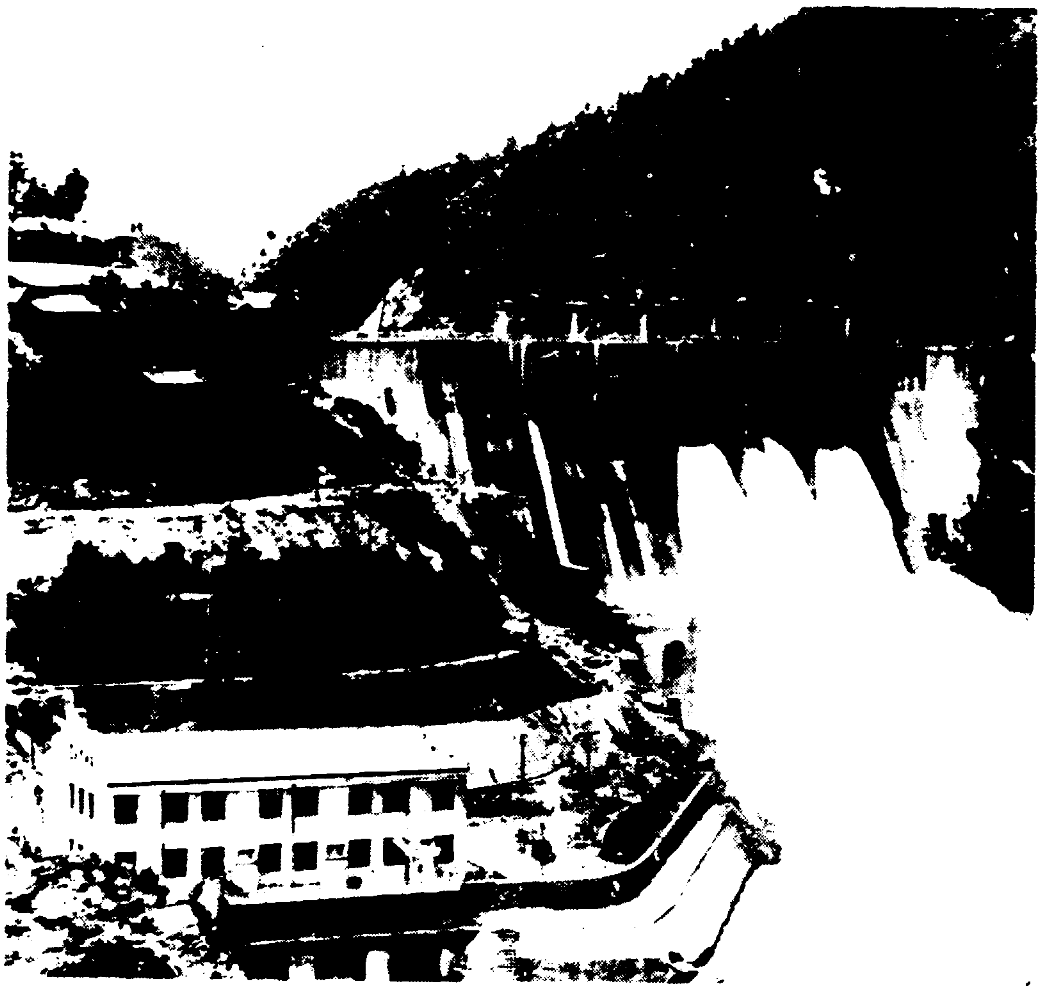
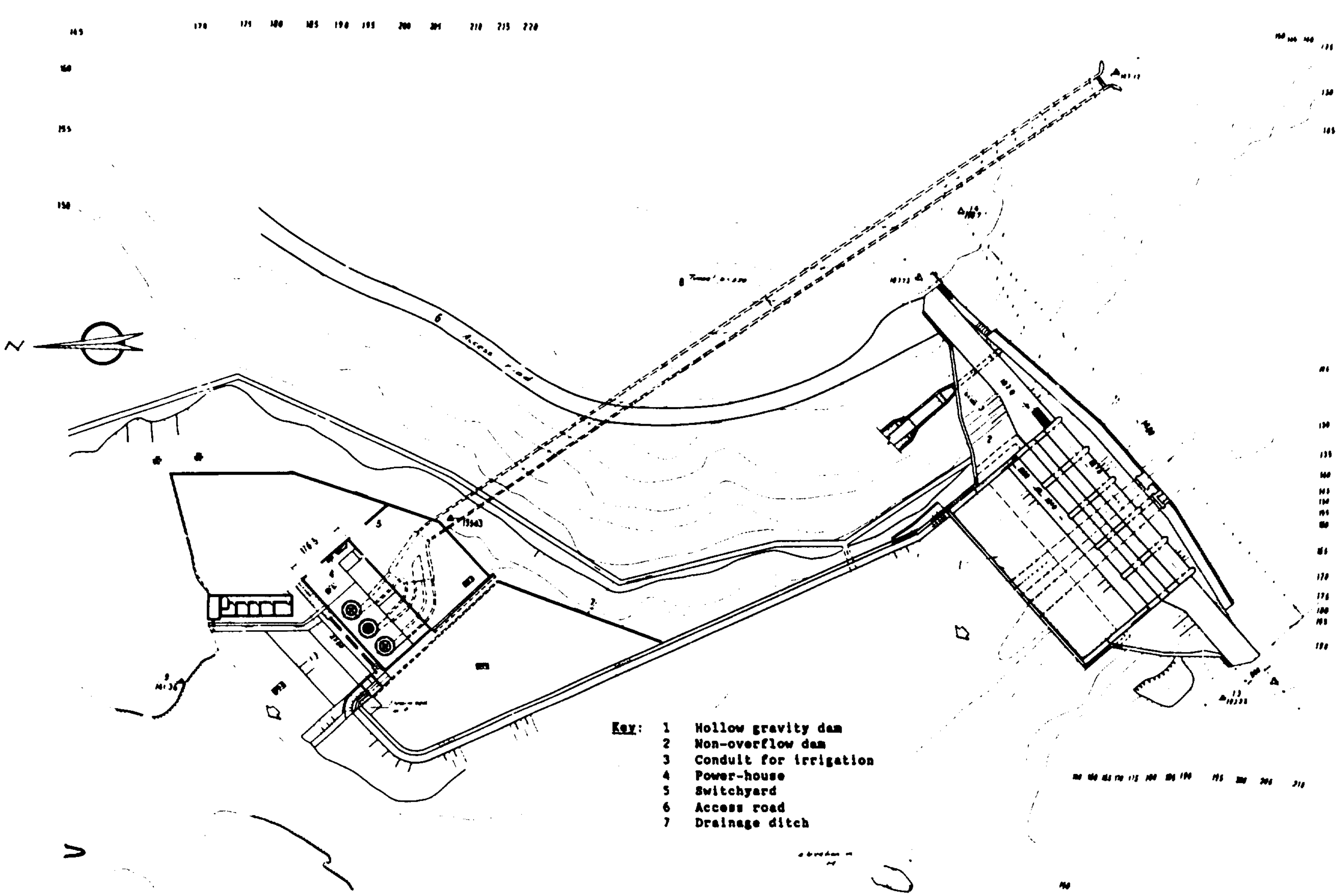
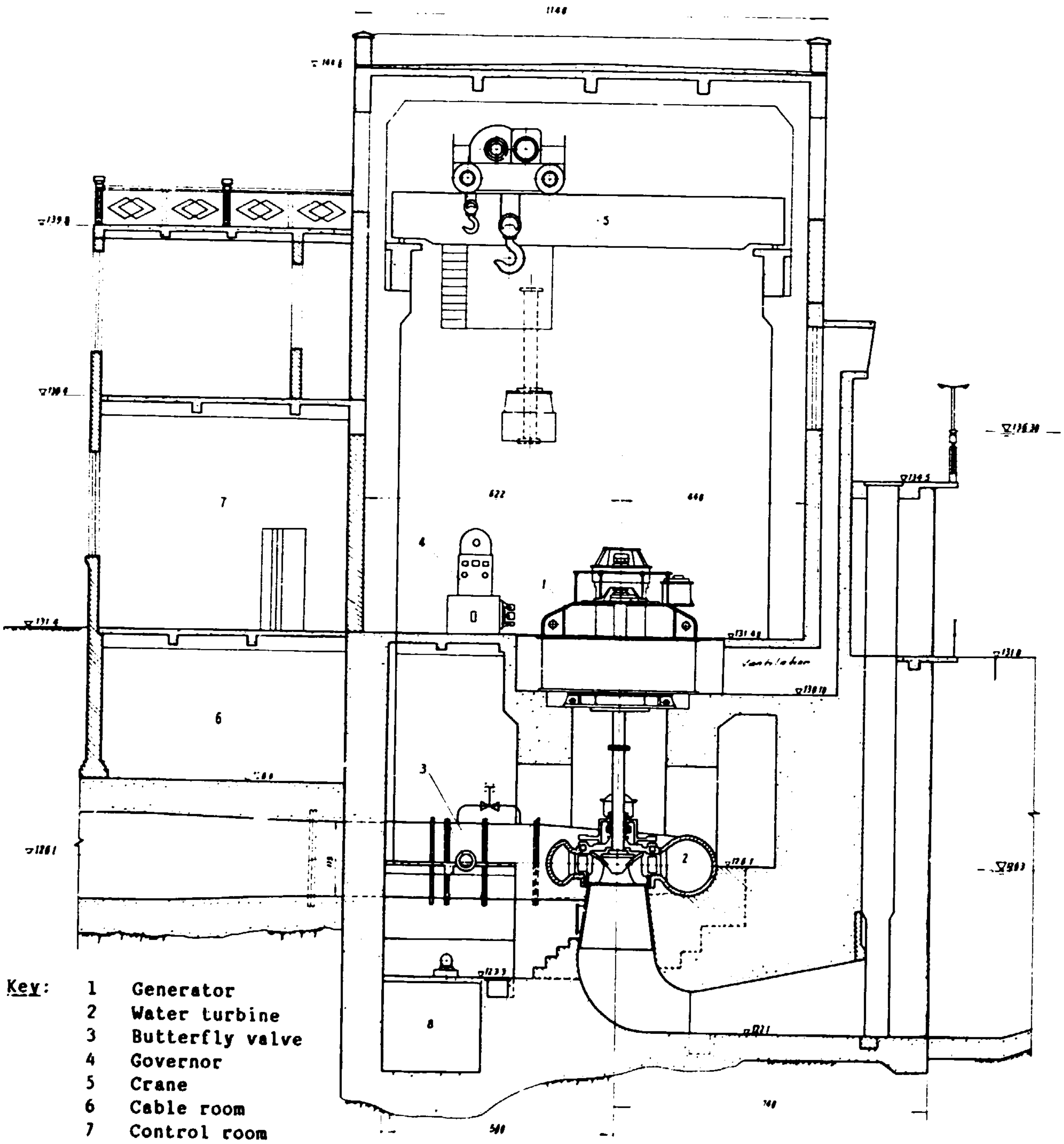


Figure 10. Yanwotan MHG station (plan)



Note: Length in centimetres, elevations in metres.

Figure 11. Yanwotan MHG station (power-house)



Key:

1 Generator
2 Water turbine
3 Butterfly valve
4 Governor
5 Crane
6 Cable room
7 Control room
8 Drainage pit

Note: Elevations in metres, dimensions in centimetres.

Figure 12. Meixi I MHG station

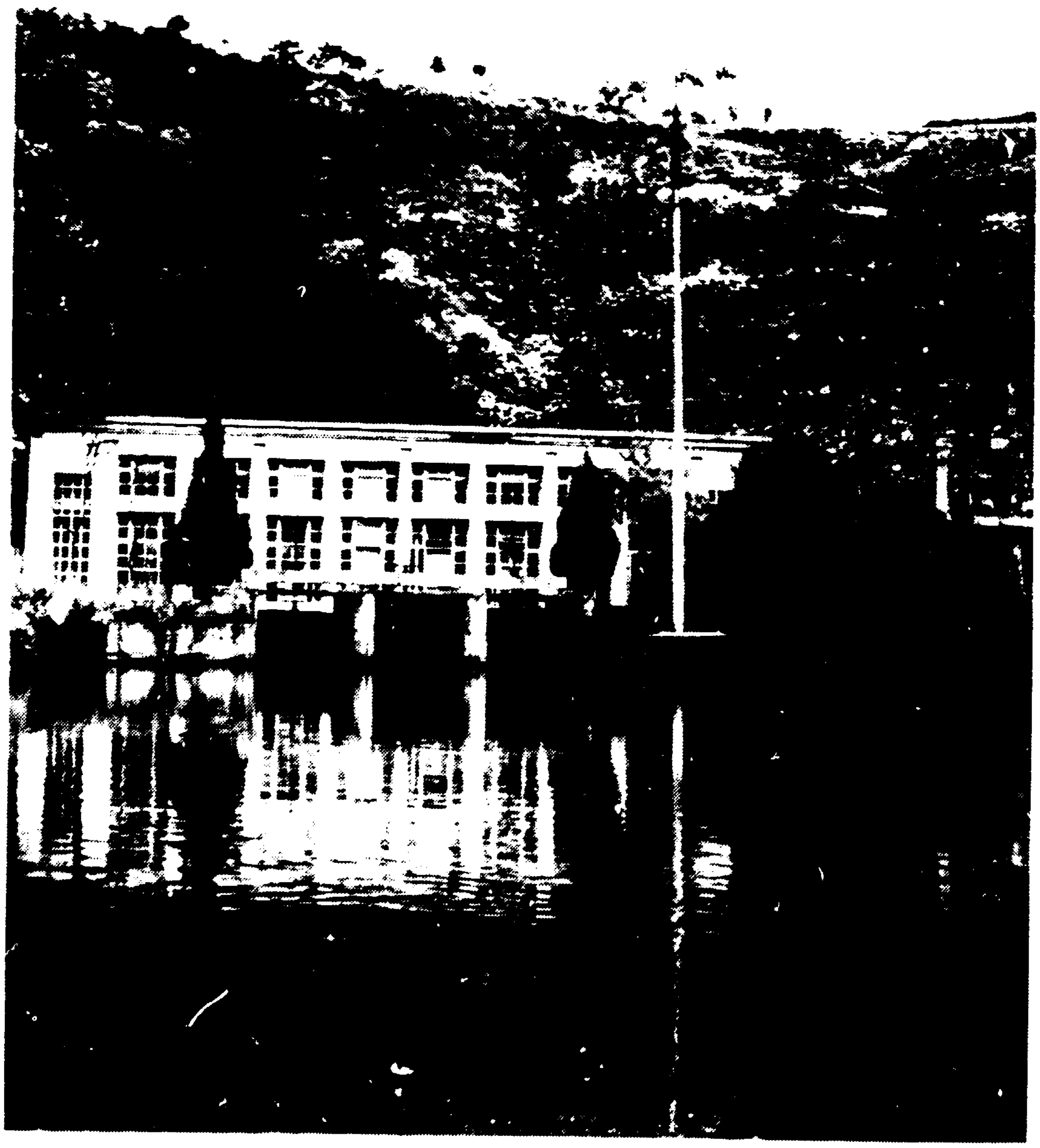
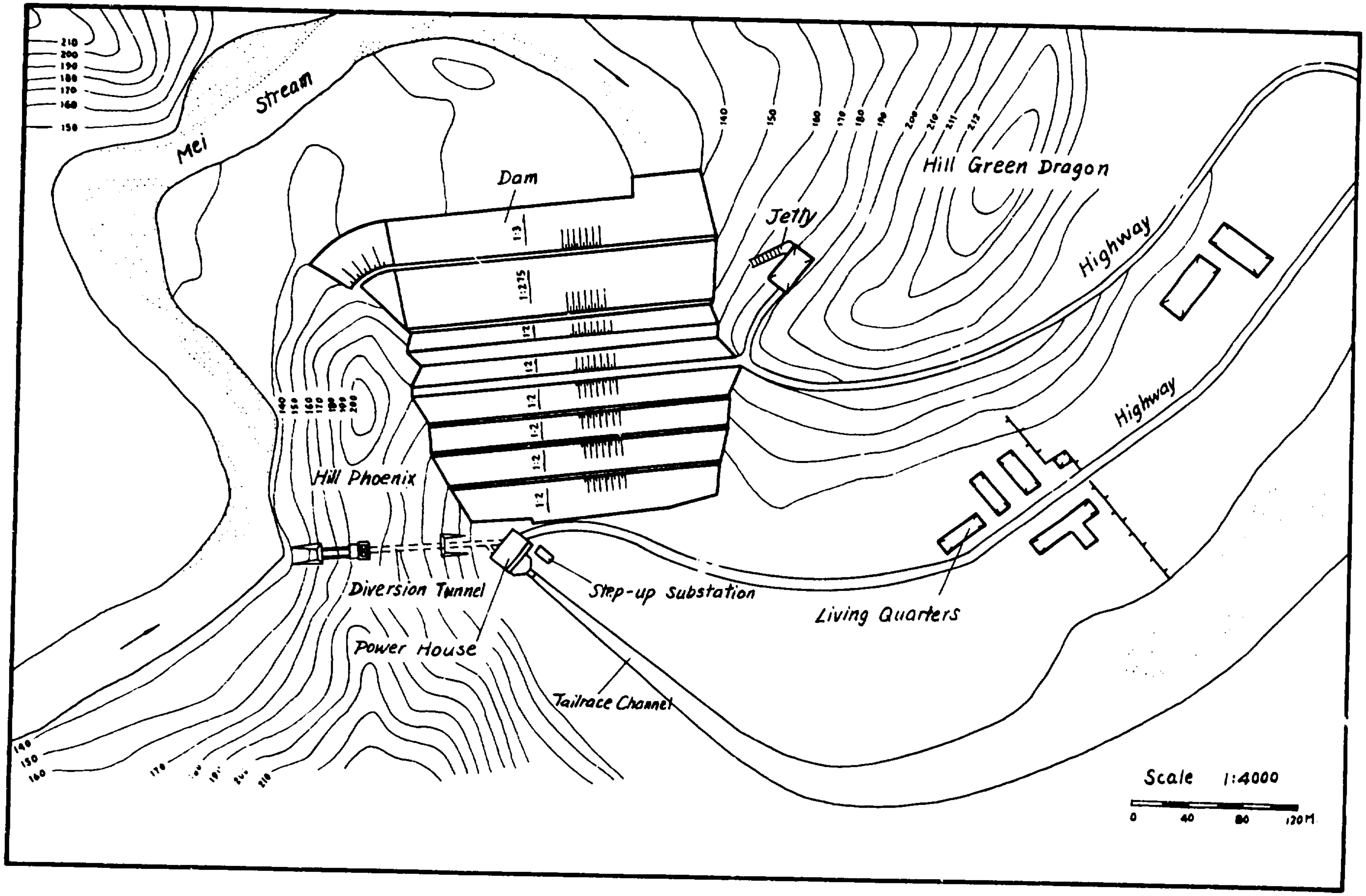


Figure 13. Meixi MHG station (layout of stage I)



In general, the special features of the dam-type hydropower plant are as follows:

(a) The dam and movable barrage are erected on the river to form the reservoir and to concentrate the head. In the case of the MHG plant, the reservoir is usually put to multi-purpose use for irrigation, flood retention and navigation;

(b) The power-house is located near the dam. Since the water conduit is rather short, hydropower plants of this kind are adaptable to a rather large design flow;

(c) If a high dam is constructed for water head concentration, then the geological conditions, the technology of dam construction and the cost of the reservoir must be taken into account.

Diversion-type plant

The head of this type of hydropower plant is formed mainly by a conduit structure. A low weir or sluice-gate is erected on the river to divert the river flow to a conduit, such as a canal, tunnel or penstock, and finally to the power-house. The type of hydropower plant is adaptable to the upper and middle reach of the river when upstream impoundment is not possible and the downstream reach contains some rapids, falls or elbows. Data on selected plants in China are presented in table 19.

Table 19. Data on selected diversion-type MHG plants in China

Plant	Location	Length of canal (km)	Penstock (m)	Head (m)	Discharge (m^3/s)	Capacity (kW)
Baizhangtan	Hubei Province	2.8		66.5	2.7	1 300
Double dragon		2.6	407	196	0.6	512
Huangtonjiang	Guangdong Province			218	1.5	2 400
Lantong	Guangxi Zhuang Autonomous region	2.8	1 100	430	3	9 600

Figure 14 shows the Qingtong hydropower plant, Guangdong Province. The plant has an installed capacity of 3 x 1,600 kW and a design discharge of 1.6 m^3/s for each of the three units. The length of the conveyance structures, including tunnels, prestressed inverted siphon pipes and flumes, is 23 km. The available head is 142 m and the penstock consists of prestressed concrete pipes 0.8 m in diameter.

Figure 14. Qingtong MHG station

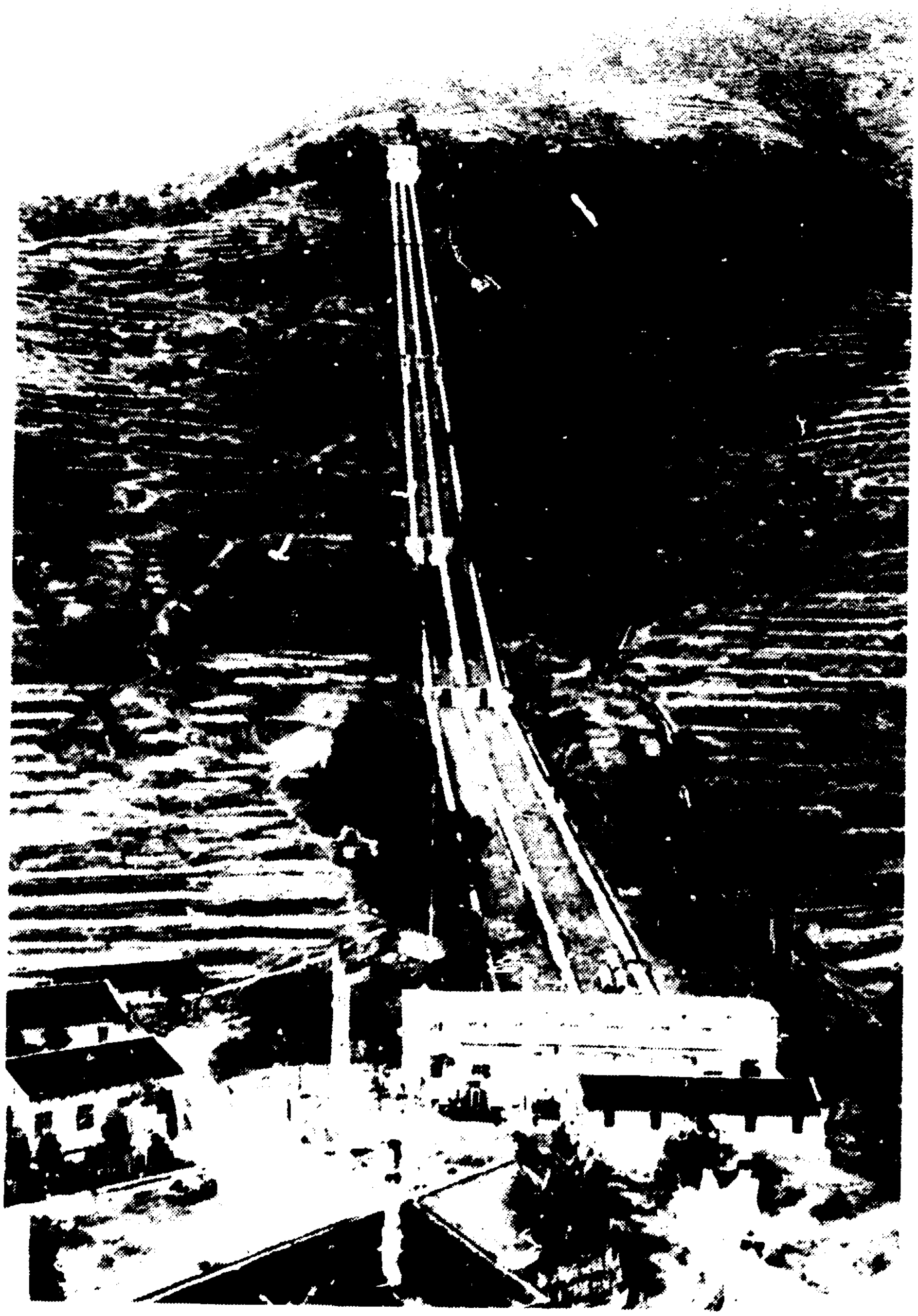
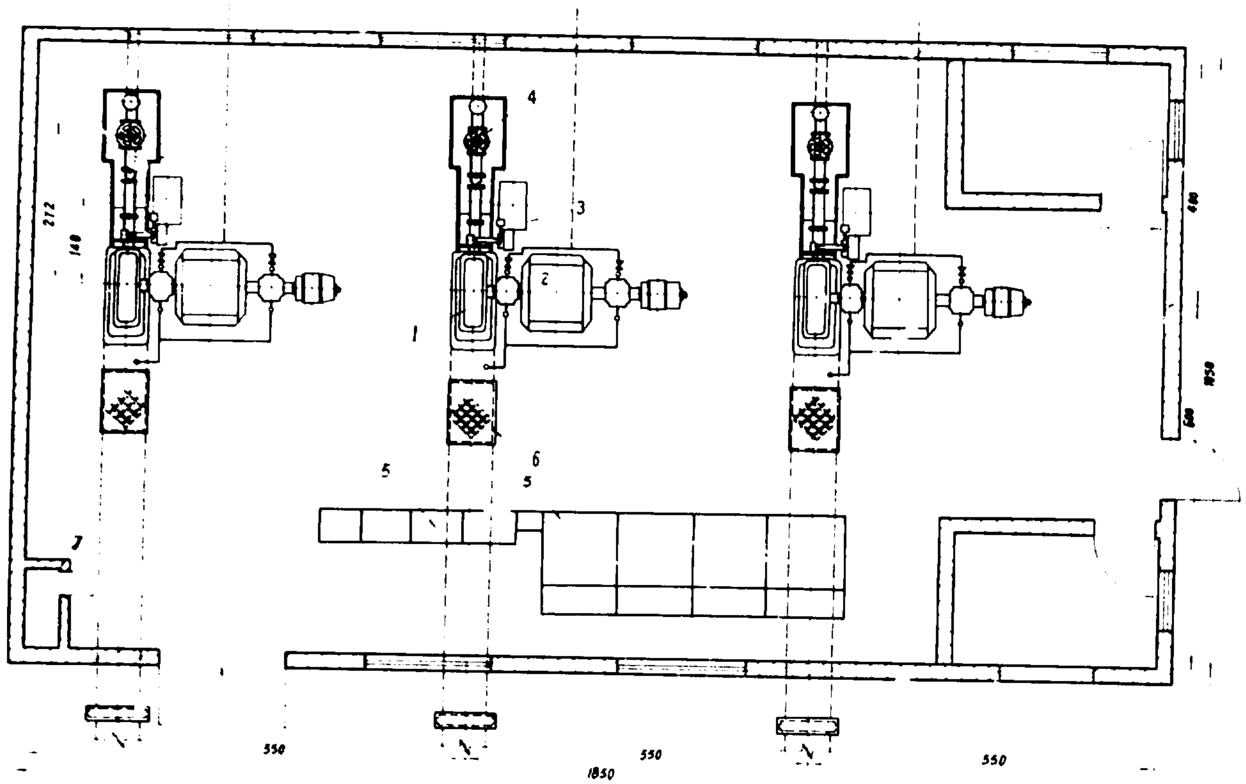


Figure 15. Chongshan MHG station (plan)



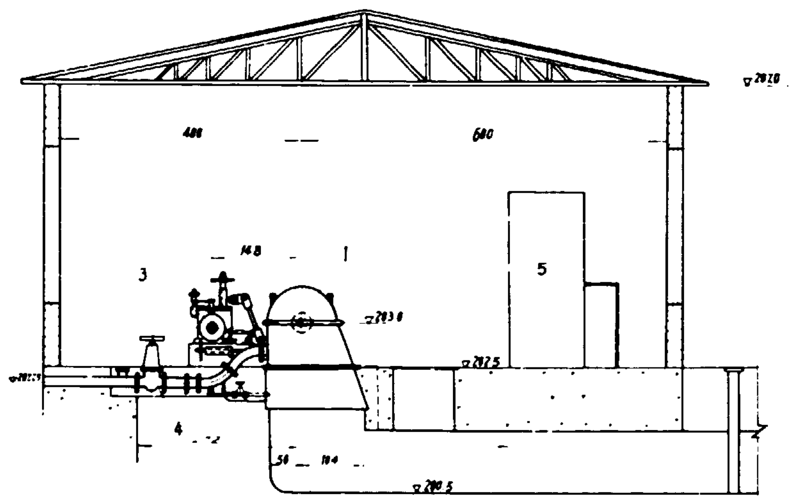
Key:

1 Water turbine
2 Generator
3 Governor
4 High-pressure valve
5 Control panel
6 Manhole
7 Battery room

Note: Elevations in metres, dimensions in centimetres.

Figures 15 and 16 show the Chongshan hydropower plant, Hunan Province. The design water head is 617 m, which is the highest among the MHG plants of the diversion type in China at present. The drainage area of the dam site is only 4.18 km^2 and the effective storage capacity of the reservoir 2.5 million m^3. The length of the canal is 1,045 m and the length of the penstock (35 cm in diameter) 1,446 m. There are 2 impulse water turbine generator units installed in the power-house, each with a capacity of 500 kW and a design flow of 0.12 m^3/s. The mean annual output is 4.17 million kWh, of which 69 per cent is used for agricultural purposes and 31 per cent for small industries and processing.

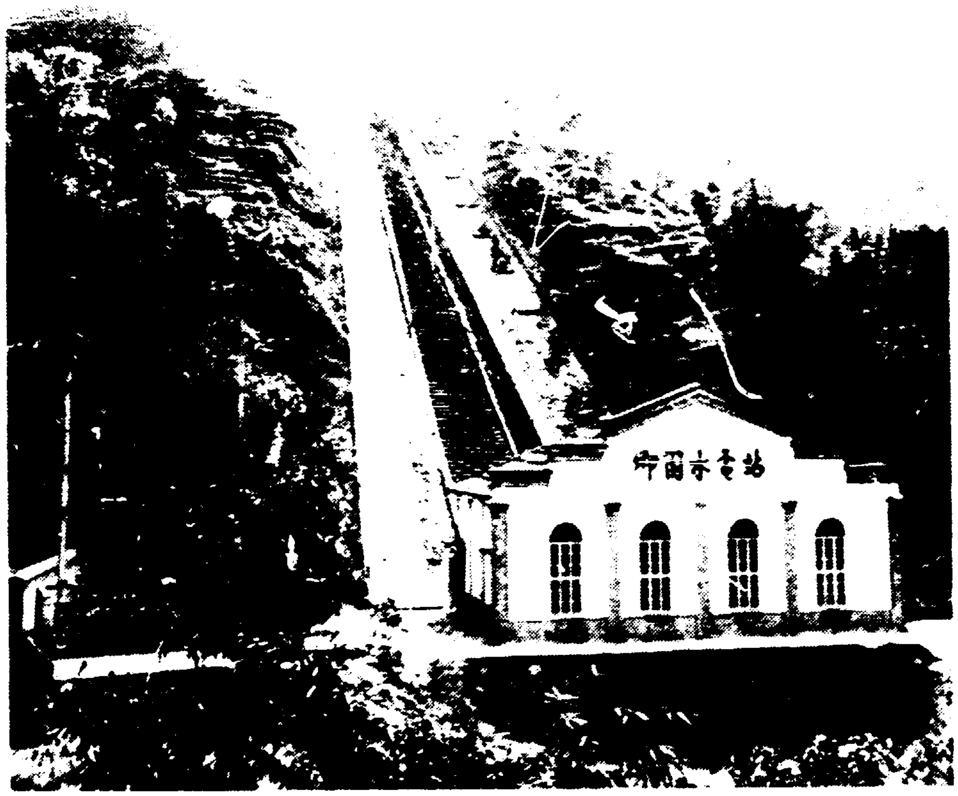
Figure 16. Chongshan MHG station (cross-section)



Note: Elevations in metres, dimensions in centimetres.

Figure 17 shows the Qing Yuan MHG plant, Fujian Province. The length of the conveyance canal is 8 km, the head concentration 46 m and the design flow 2.6 m^3/s. Three 265 kW units are installed in the power-house.

Figure 17. Qing Yuan MHG station



In general, the diversion-type MHG plant has the following special features:

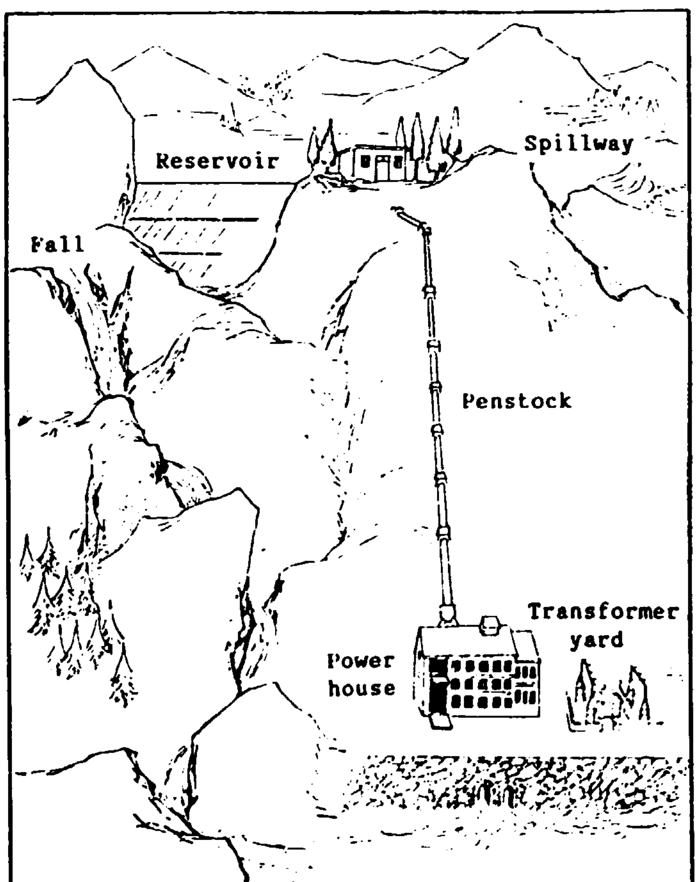
(a) In mountainous regions, if the topography is favourable, a big water head may be concentrated by conduit within a short distance. The low dam or sluice gate at the headwork of the canal intake limits the cost of reservoir impounding;

(b) here is no storage for regulation. The inflow from creeks between the dam and the hydropower-house cannot be used for power generation.

Composite-type plant

In the case of the composite-type hydropower plant, the head is obtained partly from the dam and partly from the conduit. In mountainous areas, most of the composite-type plants serve for both flood retention and irrigation, with the exception of a few plants which are planned for power generation only. Figure 18 shows the Zaixi hydropower plant, Fujian Province. The plant is located near the Wuyantou fall. Upstream of the fall is a wide valley and a flat gradient which are both favourable for storage impounding, but downstream of the fall the river has a steep gradient. Upstream of the fall an earth dam is constructed. The height of the dam is 17.2 m and the effective storage capacity 3,000,000 m^3. The power-house is located downstream of the fall. The conveyance structure is a tunnel 130 m long with a bottom slope gradient of 7.7 per cent and a penstock 418 m in length. The total head of this composite-type hydropower station is 240 m. The design flow is 2.1 m^3/s and the total capacity 4,320 kW. The main purpose of the plant is power generation. The tailwater may be utilized for irrigation and the flood attack downstream may be reduced to some extent.

Figure 18. Zaixi MHG station



On the whole, from the point of view of head concentration, hydropower plants with a dam or a conduit make up the two basic categories. The composite-type plant is a combination of the two basic types. In cases where falls, rapids, canal drops, river elbows, highland lakes or transriver basin diversions exist, the plant with a conduit or the composite-type plant are usually preferable.

Various layouts for water-power exploitation

Falls

Falls are a natural head concentration with generally small flow variations over a period of a year and substantial potential for exploitation.

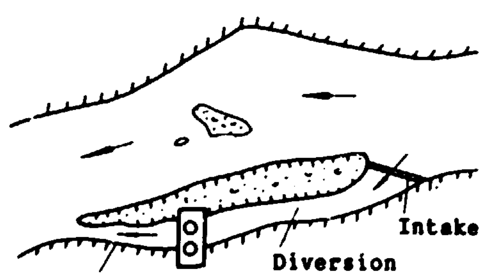
In Yunnan Province, a 40 m fall has been exploited for power generation.

In Tongchen County, Hubei Province, there are several falls near the Paizhantan. After the construction of a 400-500 m conduit, the concentrated head is approximately 140 m. Hydropower plants which utilize falls are low in cost and involve less work, which thus makes them a preferable alternative.

Rapids and natural drops

In mountainous regions, there are usually rapids or natural drops along streams and rivers which may be exploited for power generation. If the river flow is plentiful and the topography favourable, only a low diversion weir is required to divert the water without the use of the dam, as shown in figure 19. Adequate measures should be taken to protect the power-house and canal from floods.

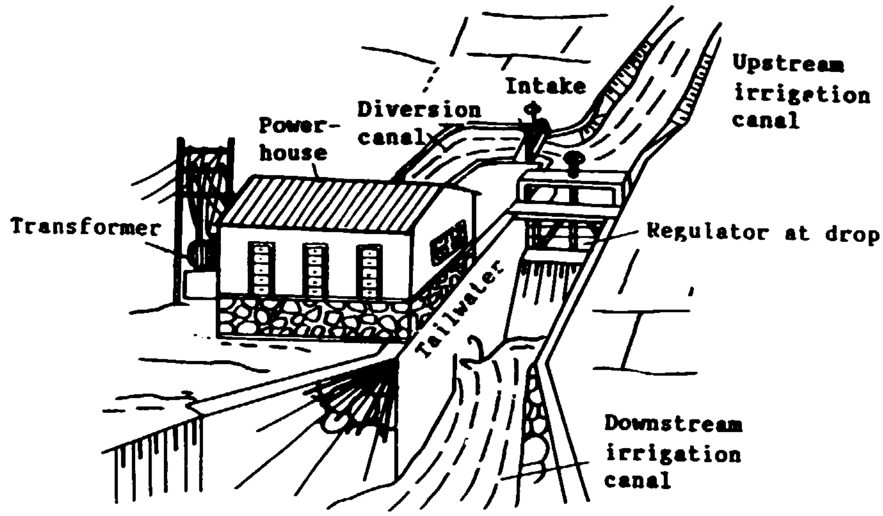
Figure 19. Utilization of rapids



Canal drops

Figure 20 is a sketch of a hydropower plant in Guangdong Province which irrigates by means of drops. The plant was constructed on an irrigation canal where all existing structures could be utilized. Only a new power-house had to be built. This method of power exploitation considerably reduces costs.

Figure 20. Separate layout of power-house and drop



Figures 21 and 22 show hydropower plants on the Mimyun-Beijing Canal. This canal conveys the water of the Mimyun reservoir to Beijing. There are eight existing drops within 30 km. The total water potential is 35 m. The water potential of the eight drops are combined into five stages for exploitation, producing a total installed capacity of 11,400 kW.

Table 20 shows the design water head and the installed capacity of 5 MHG plants on the Beijing-Mimyun canal.

Table 20. Installed capacity of cascade stations on the Beijing-Mimyun canal

Plant	Design net head (m)	Installed capacity (kW)
I	6.5	3 000
II	4.7	1 800
III	6.5	3 000
IV	4.7	1 800
V	4.5	1 800

Figure 21. Plan of hydropower station No. 3 on Beijing-Mimyun canal

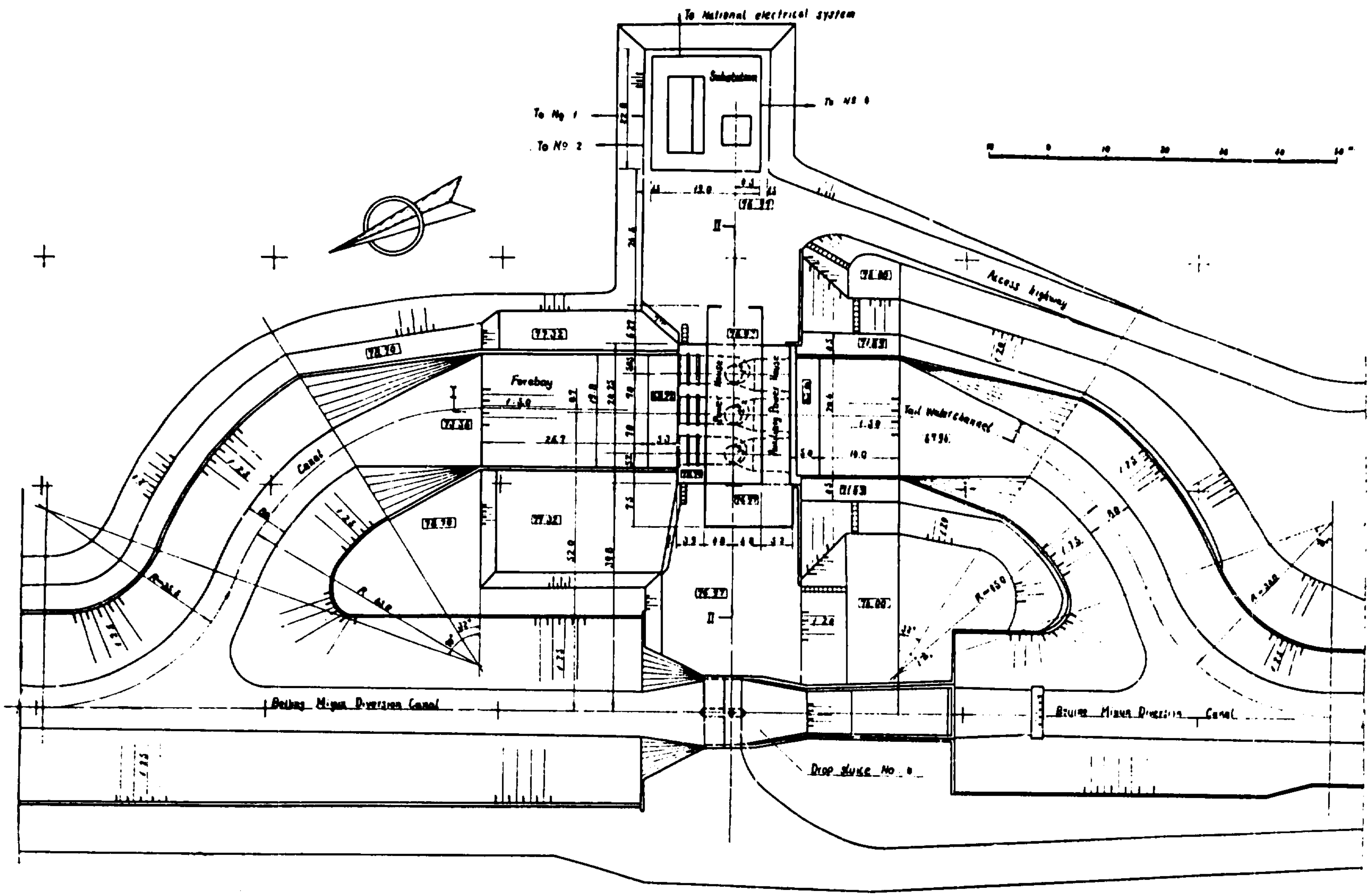
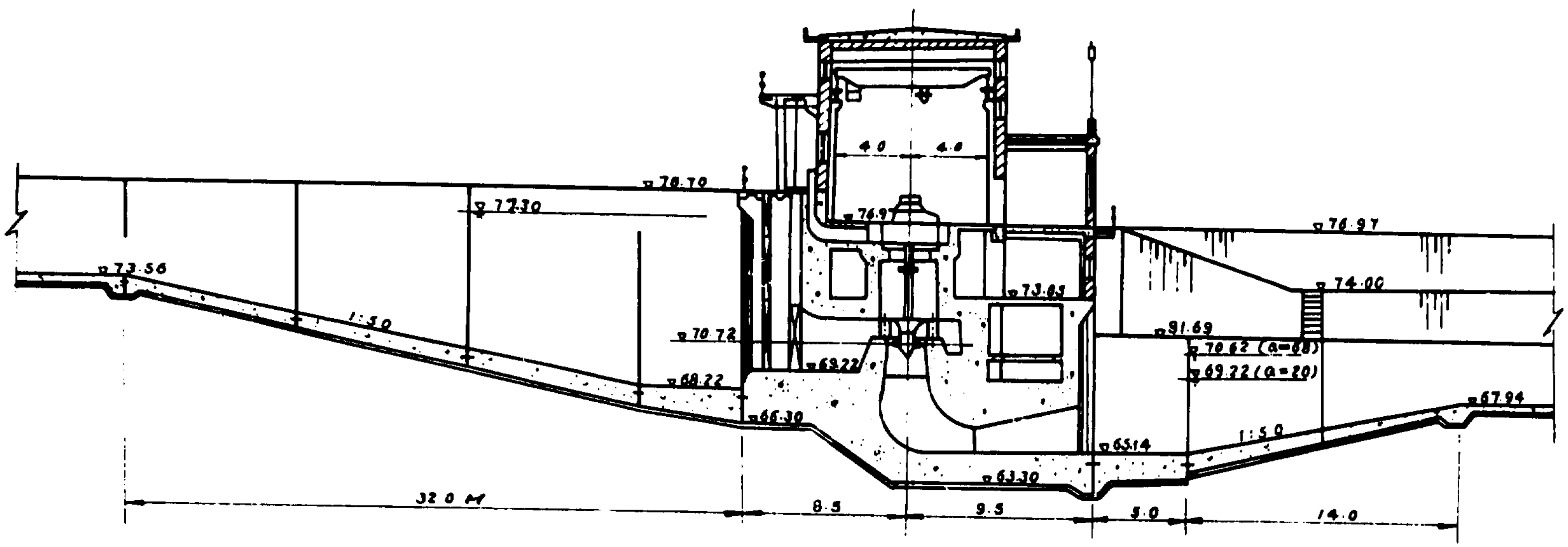


Figure 22. Cross-section of MHG station on Beijing-Mimyun canal



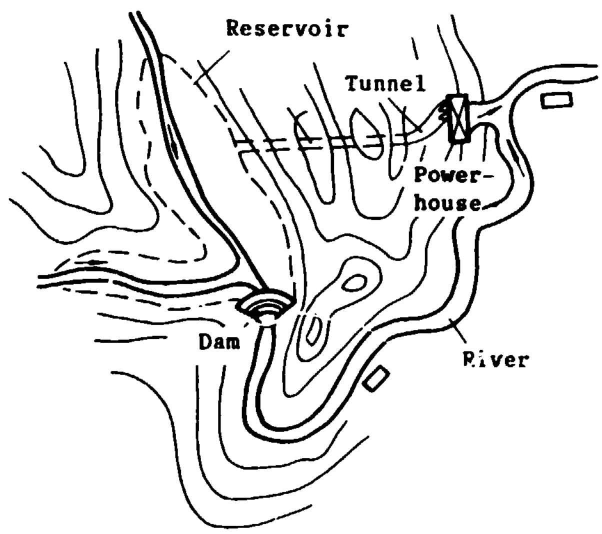
In order to minimize the types of water turbines needed and the number of sets and voltage levels for the 5 stations, the same water turbine model has been adopted in all of the stations. The model includes turbines with a working head of 6.5 m coupled with a 1,000 kW generator (250 rpm) and turbines with working heads of 4.5 m coupled with 600 kW generators (214.3 rpm). On the basis of an annual flow volume of 500-700 million m^3, the annual output of the five stations is estimated at 28-39.4 million kWh.

River elbows

Valley and river elbows are highly developed in various mountainous areas. In some cases, the river elbow looks like a ring and the river gradient is rather steep. By a short-cut conduit, a water head can be utilized for power generation.

Figure 23 shows a sketch of the Water Lane hydropower plant in Hubei Province. The length of the exploited river elbow is 7 km and a short-cut tunnel 1,580 m in length has been constructed. The head concentration is 85 m and the installed capacity 1,375 kW.

Figure 23. Water Lane MHG station

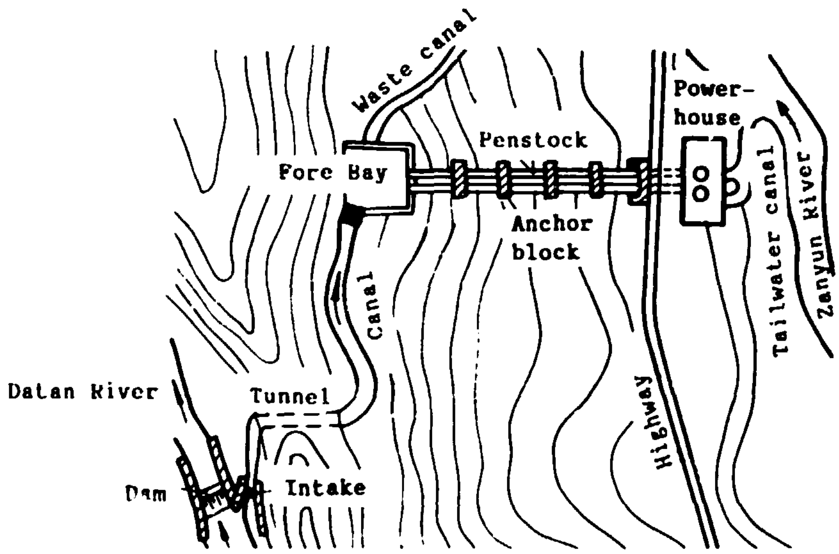


Water diversion in transriver basins

In some cases, particularly in hilly regions or river nets, the distance between the two rivers or two canals is not so far but a water head exists. Water diversion in transriver basins may be considered as a power source. Under such a scheme, the tailwater flows downstream to the lower river. The water flow of the higher river will be reduced and that of the lower river will increase. The sequence of flow-in and flow-out between the higher and lower river must be studied comprehensively from the point of view of the requirements of irrigation, navigation, water supply etc. on the downstream region. A technical and economic analysis is also necessary.

The Datan hydropower plant, Guangdong Province, is an example of water diversion in transriver basins. An 80-m tunnel and a 200 m canal have been constructed to divert the water of the Datan river to a lower small creek. The head available is 210 m and the total installed capacity 640 kW. A sketch of the plant is given in figure 24.

Figure 24. Datan MHG station



Highland lakes

If there is a river or lake near the highland lake, potential energy may be exploited by diverting the higher water to the lower river or lake for power generation.

Tide potential

China has a long seashore and many estuaries and sites where utilization of tide potential is feasible. This kind of hydropower plant has a low head and large flow but is complex to construct, resulting in larger construction costs. There are currently only a few tidal power plants in operation in China, including the following:

(a) Dalain plant, Shunde county, Guangdong Province; installed capacity of 144 kW;

(b) Kaotan plant, Xiangshan county, Zhejiang Province; tide head of about 4 m, design flow of 8.5 m^3/s, and installed capacity of 275 kW;

(c) Jing gong plant, Rushan county, Shandong Province; installed capacity of 165 kW;

(d) Liuho plant; power generated by the tides of the Yantze estuary; installed capacity of 80 kW.

On the whole, the pilot tidal power plants are small in scale.

The first pilot tidal power plant with two-directional generation in China was located at the terminal of the Luoqi Bay, Wenling county, Zhejiang Province, where tide potential is abundant with a maximum tidal head of 8.93 m. The installation of a 6 x 500 kW turbine generator unit is planned.

Submerged water or collecting springs

In Liyang county, Jiangsu Province, a production team dug water ponds in an area of approximately 50 ha in order to collect flows from creeks and brooks. The flow accumulated during the day is used for power generation in the evening. A 3.2 kW MHG plant has been built, with a head of 8 m.

In Nixing county, Jiangsu Province, a stone masonry cut-off wall was built to retain the submerged flows and raise the water level for power generation. A people's commune in Green Dragon county, Hebei Province, uses the same approach to retain the submerged flows. A plant with an installed capacity of 80 kW was constructed with a design head of 9 m and a flow of 2 m^3/s.

F. Electrical scheme and step-up substation

The electrical design of MHG stations is not much influenced by variations in natural conditions. Hence, in spite of special features in small stations in different places, the electrical designs are basically the same.

For MHG in China, the voltage of a generator set with a capacity of less than 500 kW is generally 400 V, which is transmitted at 10.5 kV through a step-up transformer. The transmission radius of such a station is not greater than 15 km. The voltage of generator units at a capacity of 500-6,000 kW is generally 6.3 kV. Three levels of out-feeding voltage, i.e. 6.3 kV, 10.5 kV and 38.5 kV, may occur in such stations. In a few places, 110 kV are applied.

The transmission voltage of 6.3 kV adopted in previously constructed stations has recently been replaced by 10.5 kV. The 3.15 kV voltage level used previously has also been discontinued.

Various types of electrical schemes are used in China, the most frequent ones being the following:

(a) Single bus scheme at generator voltage, sectioned and unsectioned (figures 25 and 26);

(b) Block of generator - transformer (figure 27);

Figure 25. Single bus scheme (unsectioned)

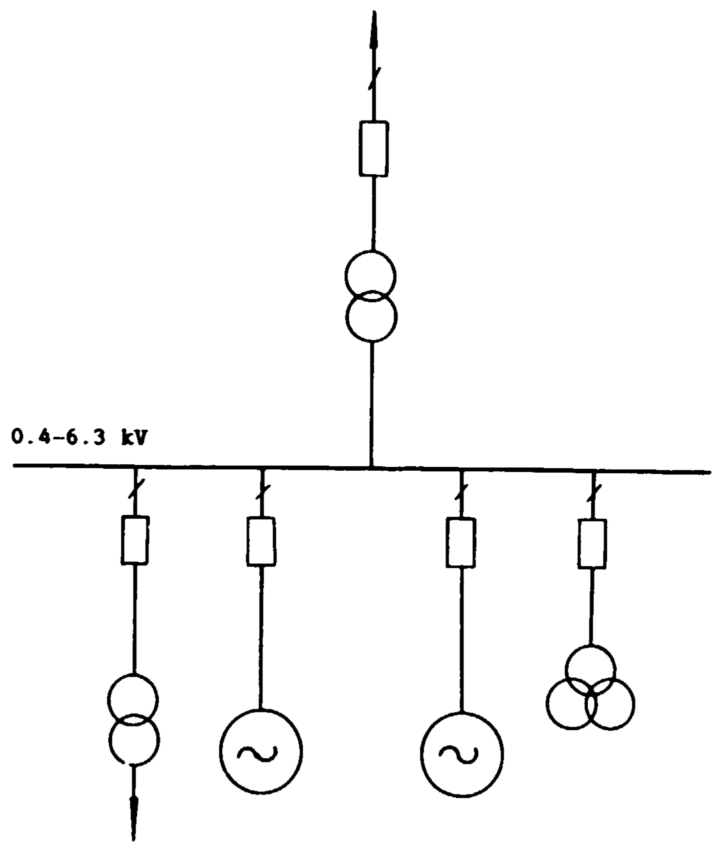


Figure 26. Single bus scheme with 6.3 kV (sectioned)

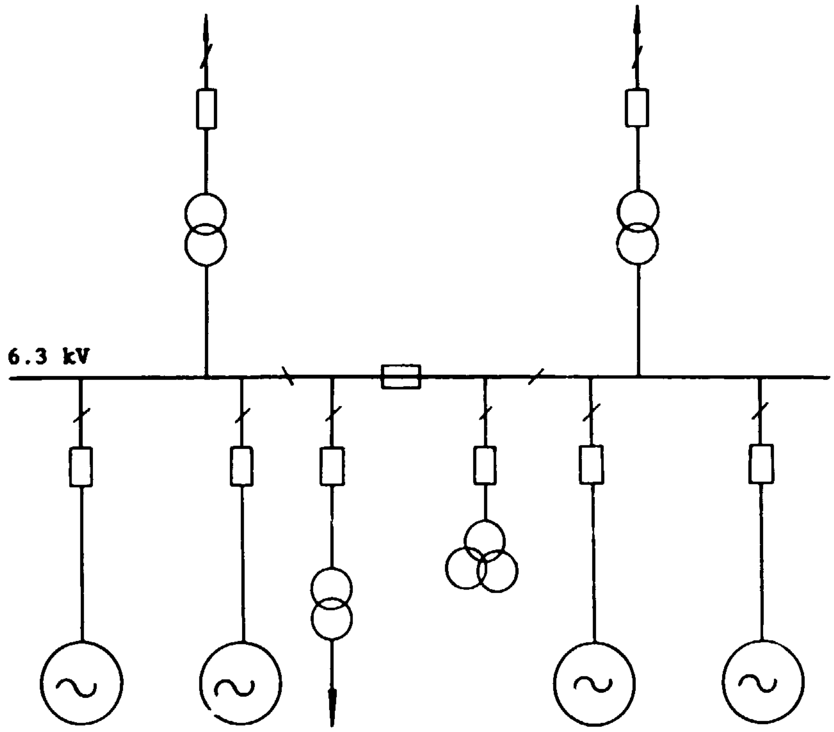
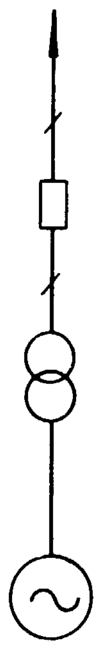


Figure 27. Generator-transformer block



(c) Step-up substation at voltage 38.5 kV or 10.5 kV:

(i) Bridge connection (figure 28);
(ii) Single bus (figure 29);
(iii) Block of transformer line (figure 25).

Various electric schemes may be designed by combining the above unit blocks.

All high-voltage equipment required for a power station in China can be produced in that country. All except very few provinces and autonomous regions have manufactured their own electrical equipment.

Complete switching sets are used for most 6.3 kV electrical facilities, in which circuit breakers, disconnection switches, instrument transformers, metering and some relay protection and operating components are installed according to various composite schemes of primary and secondary wiring. These are provided to customers in complete sets. There are dozens of varieties of seriation schemes of complete switching sets available for selection by the designing personnel of MHG stations. Outdoor types are generally used for 38.5 kV electrical facilities, which are usually assembled in outdoor substations.

A similar design standard of relay protection, including differential, overcurrent, overvoltage, overload and grounding fault protection, is used in MHG stations in different places. The relay protection components usually used in China have been electromagnetic types. Transistor relay protection components have been tried at a few stations.

There are also numerous ways of controlling MHG stations. The types most adopted are as follows: a central control room (generally used in comparatively large stations); on-site control of a generator room with a special control and metering panel; and on-site control in a generator room using complete switch sets. The latter two types are usually used in rather small stations. The d.c. operating voltages are usually 220 V, 110 V and 48 V.

The degree of automation in MHG stations in China is not very high. In stations with a capacity of 500-12,000 kW, the following automatic operations can generally be realized: automatic regulation of frequency and voltage; centralized operation for starting and stopping the generator sets and for regulation of loads; automatic warning on electrical and mechanical accidents and malfunctioning; and automatic operation of some auxiliary devices in the stations.

The electrical scheme, wiring and components used in automation are generally still of the electromagnetic type. There are few places where trial operation of semiconductor elements and logic circuits are taking place. The telemechanization of MHG has not yet been tried.

According to the specific conditions in China, the main objectives of automation of MHG are to ensure the quality of electricity, to increase the reliability of electricity supplies, to improve safety, to reduce labour intensity and to decrease the number of personnel needed for operation.

Most of the stations currently integrated in grids of different levels have been equipped with communication facilities in connection with the local dispatching centre. Many stations with a 35 kV outline voltage have adopted carrier telephone on power lines.

Figure 28. Bridge scheme

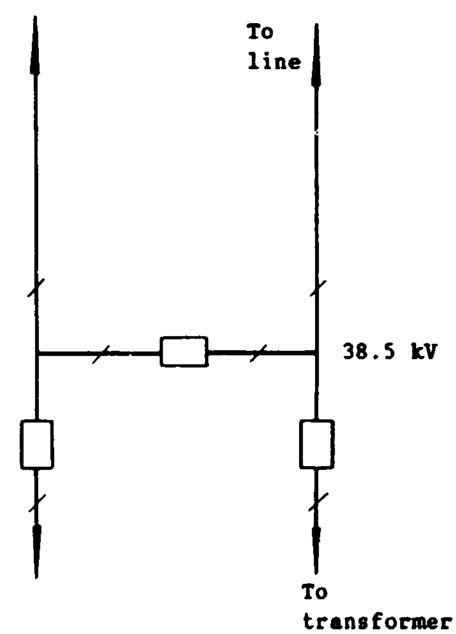
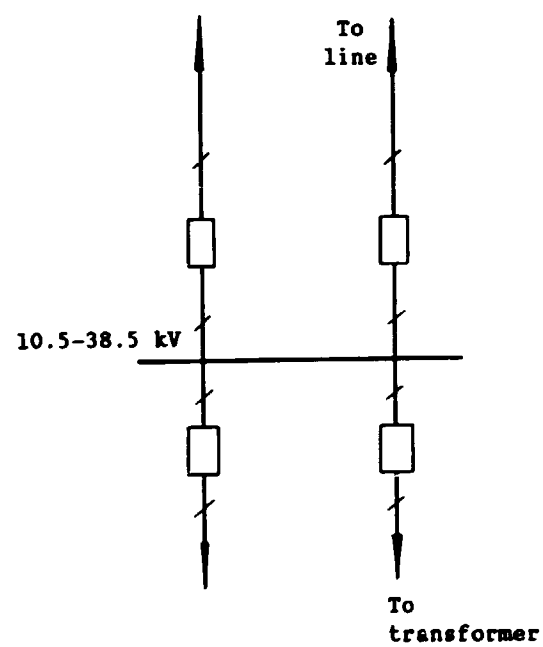


Figure 29. Single bus scheme with 10.5-38.5 kV



IV. HYDROELECTRIC EQUIPMENT

A. Hydroturbine generator sets

China now manufactures a fairly complete range of small hydroelectric equipment. It has equipment both for high head operations up to 612 m, suitable for the development of mountainous regions, and for large discharge and low head up to 2 m in low-lying areas. Standard designs are currently available.

According to a new regulation, hydraulic turbines are classified into three main categories, including 27 series and 85 different types (see table 21). The 16 generator supports include 121 different types. In order fully to utilize widely dispersed water power resources and to supply electricity to remote and mountainous regions, the manufacturers produce a special series of 0.25 to 75 kW mini-unit sets. Because the mini-unit sets are small in volume, light in weight, simple in construction and low in cost, they are much appreciated by people residing in mountainous regions. Owing to the shortage of reactive power in the rural grid, synchronous generators are used mostly in MHG.

The requirements of standardization, popularization and serialization are important for China, which has so many diversified hydrological parameters. The advantages of these products are that they are simple to manufacture, suitable for mass production, high in productivity, good in quality, low in cost and easy to operate and maintain.

China has produced over 200,000 sets of hydroelectric equipment. A portion of them have been exported and the rest installed in more than 80,000 small hydroelectric stations scattered over a vast region. Some of them have been in operation for more than 20 years. Judging from their operating conditions, it has been proven that they are sound in quality and adapt very well to the varying operating conditions in different localities. For example, two 612 m head, 500 kW, CD10-WJ-90/1 impulse-type units have been safely operating in the Zhong Shan hydroelectric power station, Dayong county, Hunan Province, for more than 10 years. The condition of cavitation is satisfactory. The Jinghua No. 1 hydraulic turbine, through repeated operation and comparison, has proven to be of good quality and been used as a standard of reference. A GZN 005-WP-250 double-flow turbine generating unit has been produced and installed in the tidal hydroelectric power station in Wenling county, Zhejiang Province. In recent years, many provincial manufacturers have produced large numbers of equipment for small hydroelectric stations. Some of the units have already withstood the most severe operating conditions.

Investigations made on small hydroelectric machines and equipment after long periods of operation have revealed that equipment made in China is well-constructed and of good quality. Data on a number of hydroelectric stations which have had satisfactory operating records for many years are given in table 22.

The production of small hydroelectric machines and equipment in China has been developing very rapidly. Productive capability currently exceeds 1 million kW. A whole set of equipment can be supplied upon request. Although the equipment is mainly for the home market, some is supplied to foreign countries.

Table 21. Various types of hydraulic turbines manufactured in China

Serial Number	Operating range Head (m)	 Flow (m^3/sec)	 Capacity (kW)
ZD760-LM-40,60,80,100, 120	3.5-7	0.45-6.8	12-400
ZD760-LMY-100,120	2.7-7	2.96-8.6	55-400
ZD560-LMY-40,60,80	4-14	0.568-3.45	12-400
HL260-WJ-25,30,35,42,50	9-29.7	0.235-2.45	12-500
HL220-WJ-42	24-50	0.95-1.375	200-500
HL110-WJ-30,35,42, 50,60	20-70	0.159-1.07	20-600
CJ22-W-45/1x4.5, 55/1x7 55/1x5.5 70/1x9	50-330	0.055-0.401	20-630
XJ13-W-25/1x7, 32/1x7 32/1x9, 40/1x9 40/1x11, 50/1x12	36-160	0.084-0.66	21.5-826
XJ02-W-63/1x16	75-220	0.761-1.262	400-2 000
CJ22-W-110/1x12.5 110/2x12.5	220-340	0.781-0.970 1.446-1.942	1 250-2 500 2 000-5 000
CJ22-W-125/1x12.5	300-504	0.910-1.186	2 000-5 000
HL240-WJ-71	29.5	3.2	750
HL240-LH-120	18-23	7.23-9.13	1 000-2 000
HL240-LJ-12)	20.1-37	8.06-10.85	1 250-3 200
HL240-LH-180	18.5-33.5	17-23.2	2 500-6 300
HL160-LJ-100	84-114	6.01-6.83	4 000-6 300
HL160-WJ-71	71.8-112.6	2.81-3.54	1 600-3 200

continued

Table 21 (continued)

Serial Number	Operating range Head (m)	 Flow (m^3/sec)	 Capacity (kW)
HL200-LH-100	67-90	7.81-8.97	4 000-6 300
HL260-WJ-71	21.3-28.7	3.32-3.86	500-800
HL260-LH-100	19-25	5.7-6.6	800-1 250
HL220-WJ-50	30-70	1.48-2.3	400-1 000
HL220-WJ-71	32-78	3.14-4.33	800-2 000
HL220-WJ-84	30-55	4.33-5.91	1 000-2 500
HL110-WJ-60	100-145	1.4-1.52	1 000-1 600
HL110-WJ-100	120-200	4.1-5.6	4 000-6 000
HL100-WJ-71	222-315	1.58-2.4	3 200-6 000
ZD560-LM-180	9-16	15.8-23.02	1 000-2 500
ZD560-LM-250	10.6-15.5	31.4-44	2 500-5 000
ZD510-LH-180	6.5-14.5	13-18.8	600-2 000
GD103-WP-275	4.5-8	39.2-57.6	1 320-3 600

Note:
HL - Mixed-flow-reaction-type
XL - Inclined-tubular-type
ZD - Axial-flow reaction fixed-blade propeller-type
XJ - Cross-flow-type
CJ - Impulse-type
GD - Tubular-fixed-blade-type
W - Horizontal shaft
L - Vertical shaft
J - Metal spiral casing
H - Concrete spiral casing
P - Bulb
M - Open flume
Z - Tubular-type

Table 22. Operating conditions of various types of Hydroelectric generating units

Station	Location	Installed capacity: Units x kW	Installed capacity: Head (m)	Design flow (m^3/s)	Turbine	Generator	Operating time (years)	Remarks
Baizhangtan, second stage	Hubei Province	2 x 500	26-35	2.2	HL260-WJ-60	TSW-99/37-6	5	Smooth operation
Xianggongdong	Hunan Province	3 x 300	580	0.1	CD10-WJ-90/1	TSW-99/40-6	13	Normal operation for a long time
Xiayuan	Zhejiang Province	2 x 500	126	0.484	CJ-W-90/1x11	TSW-143/32-12	13	Normal operation, good performance, easy maintenance
Pangi, second stage	Zhejiang Province	2 x 800	220	0.5	CJ-W-90/1x11	TSW-143/43-10	6	Normal operation, good performance, easy maintenance
Mabu	Guangdong Province	2 x 3 000	122.7	3	HL160-WT-71	TSW-146/60-6	6	Good performance
Niuwan River	Guanyang	2 x 320	50	0.77	HL110-WJ-60	TSWN-85/39-8	11	Normal
Landong	Rongchen	3 x 3 200	415	1	GJ-W-125/1x12	TSW-173/86-10	3-5	Normal
Gunapi	Guangxi Province Yangshan Guangdong Province	6 x 800	184	0.6	GJ-W-92/1x11	TSW-143/44-10	15 (installed in stages)	Normal
Mayang, second stage	Zhejiang Province	2 x 1 600	25.7	0.79	HL260-WJ-35	TSWN-59/41-6	8	Normal operation, high output
Baizhangji, first stage	Zhejiang Province	2 x 12 500	336-354	4.7	CJ-W-146/2-140	TSW-256/115-2	20	Good performance, continues to operate
Jiuguan	Fujiang Province	4 x 800	13	8.19	ZD560-LH-120	TSN-215/21-14	5	Normal
Majilong	Zhejiong Province	1 x 75	6	1.5	ZD760-LM-60	TSN-59/27-8	19	Normal
Feishuiyan	Zhejinag Province	2 x 160	78	0.44	XJ02-W-42/1x10	TSWN-74/29-8	6	Normal
Dongguan, second stage	Fujian Province	2 x 1 250	43	3.5	HL220-WJ-71	TSWN-143/61-10	10	Normal

The serial number HL 110-WJ-35 may therefore be interpreted as follows:

```
HL      110      W     J     35
|        |       |     |     └─Nominal runner diameter 35 cm
|        |       |     └─Metal spiral casing
|        |       └─Horizontal axis
|        └─Runner model 110 (specific speed)
└─Mixed-flow-reaction-type
```

B. Main auxiliary equipment

In China, the manufacturers of hydropower machinery are responsible for providing main auxiliary equipment, including speed governors, excitation facilities and automatic components, in addition to the main generating sets.

According to the manner of operation, there are five types of governors used in MHG, namely, manual, electrical, hydraulic-electrical, electronic-electrical and electronic-hydraulic. The number of serials comprised in the standard set is eight. These are listed in table 23.

Table 23. Standard speed governors manufactured in China

Model	Capacity (kg-m)	Type
TT-35	35	Single-regulation, direct flow
TT-75	75	Single-regulation, direct flow
TT-150	100-220	Single-regulation, direct flow
TT-300	230-375	Single-regulation, direct flow
YT-300	230-375	Single-regulation, hydraulic-electrical
TT-600	450-760	Single-regulation, hydraulic-electrical
YT-1000	760-1 720	Single-regulation, hydraulic-electrical
CT-40	2 000-3 720	Single-regulation hydraulic-electrical

The speed governor of YT-serials is an automatic governor designed in China and specially adapted to MHG stations. It is equipped with an automatic flying pendulum and two servo-motors which are capable of automatically regulating the speed of the turbines and of controlling start-up and shut-down of the turbines from a distance, as well as regulating load. In addition, there is an electromagnetic valve for emergency stops. The valve can be operated by a d.c. current which controls the hydraulic passage for prompt shutting-down of the generating set and prevents accidents in case of an emergency at the station when the a.c. source is interrupted. If the hydraulic system of the speed governor happens to fail during normal operation, manual operation is possible by means of a specially equipped hand wheel or lifting rod. The fluid and air filling of the pressure tank of the TY-type governor can be automatically carried out without the help of an outside air compressor which is required for ordinary governors. Such features are well suited for MHG stations which are often only equipped with simple facilities.

There are many types of excitation for generators. In the past, d.c. exciters with electromagnetic regulators were mostly used. For generators of less than 100 kW, only a resistor is equipped in the magnetic field to control the excitation.

Recently, many types of updated excitation facilities have been produced in China, including a SCR excitation with a transformer at the outside terminal of the generator as a power source, a triple-winding phase-shift compound excitation and a silicon rectifier with a double-winding generator shunted by a reactor. These products have been examined in different places under various modes of long-term operation and proven to be reliable. They have therefore been widely used throughout the country.

In some places, old stations have been renovated with new electronic facilities, as in Laoding county, Guangdong Province, where 70 per cent of the generators are equipped with SCR excitation.

Since the early 1970s, hydropower generators of 630-1,250 kW, with third harmonic voltage excitation through SCR, have been produced and installed in several stations. Several years of operation have proven the reliability of the excitation equipment, which, in comparison with electromagnetic excitation for generators of the same size, not only saves over 50 per cent in cost and 50 per cent in copper, but also performs better as a self-forced excitation affected very little by variation of frequency.

In addition, brushless excitation devices, which are in common use outside China, have been manufactured and installed in some stations in China. A serial scheme of SCR excitation for generators with a capacity of 500-5,000 kW is also being developed.

C. Equipment supply

The provision of complete sets of the main electromechanical equipment required for MHG has been arranged by the Government and some provinces. It includes the main equipment and its auxiliaries, transformers, high-tension switchgears, various control and protecting panels, cables, cranes, air compressors, pumps, porcelains etc. In Sichuan Province, a corporation for the manufacture of power plant equipment has been set up to incorporate 90 or more manufacturers of power plant facilities through specialty co-ordination. Such corporations are also being established in Zhejiang and Guangdong Provinces.

V. RESEARCH, DEVELOPMENT, TRAINING AND THE COST OF MHG

China has trained many technical teams in the implementation and management of MHG plants, particularly in areas such as planning, exploration, design, construction, installation, operation and maintenance. Efforts are being made to raise the level of technology, to carry out research, to improve the reliability of the power supply and to reduce construction costs.

A. Research

Pre-stressed concrete pipes

In the past, the high- or medium-pressure pipes used in MHG plants were usually made of steel. The supply of steel, however, was not adequate to meet the needs of hydropower development. In 1964 the Gaoliang MHG station, Guangdong Province, used self-made spigot-and-socket-type pre-stressed concrete pipes instead of steel pipes. Soon afterwards, all plants gradually began to do the same.

Up to that time, cement pipe plants had manufactured pressure pipes 76 km in total length for 2,700 hydroelectric units. The highest water head is at the Huangtongjiang station, Guangdong Province, which reaches 218 m. Three 800 kW generating units have been installed and 600 mm pre-stressed concrete pipes used. At the Shiuxia MHG station, which has a water head of 168 m, four 3,000 kW generating units have been installed and pre-stressed concrete pipes 1,250-1,300 mm in diameter adopted.

The advantages of pre-stressed concrete pipes in comparison with steel pipes are as follows: low cost and consumption of steel; durability; and convenience of installation and better water-sealing of joints.

Generally, the consumption of steel can be lowered by 70-90 per cent and the cost by 60 per cent when pre-stressed concrete pipes are used instead of steel penstock (those with low head and large diameter may save even more steel and cost). For example, at the Shuixia MHG station, about 175 tonnes of steel costing approximately ¥RMB 310,000 were required for the steel penstock design, but only 53 tonnes of steel and ¥RMB 120,000 were needed to manufacture the pre-stressed concrete pipes. Thus, savings in steel and cost were approximately 70 per cent and 61 per cent, respectively.

All pre-stressed concrete pipes were tested by means of a water pressure test. After keeping the pipes under constant pressure for 24 hours, the tests revealed that a maximum water pressure of 34 kg/cm^2 was possible without danger of cracks and leakage. After four years of operation the pre-stressed concrete pipes were still in good condition.

In China the first pre-stressed concrete pipes were put into operation in 1964. When this study was carried out those pipes continued to perform as well as at the time of their installation. On the other hand, at an MHG station with a working head of 120 m, a steel penstock with a diameter of 0.4 m was installed in 1958. Owing to erosion as well as to the small diameter of the pipe which made maintenance impossible, the steel pipe ruptured under inner water pressure. It was then replaced by a pre-stressed concrete pipe which worked without complications.

The spigot-and-socket-type is easy to install. The important point is to lay a rubber seal in the spigot end and then put the spigot into the socket. This technology results in secure sealing and promotes high efficiency in installation. For example, in one MHG station with a head of 200 m, after four years of operation the seal of the spigot-and-socket joint was still in excellent condition. The joint is also more capable of adapting to deformation.

Another advantage of pre-stressed concrete pipes is their low maintenance cost. However, they have shortcomings such as a larger dead-weight and the fact that they break more easily during transport and installation. Adequate measures should be taken to overcome these problems.

Design of pre-stressed concrete pipes

Pre-stressed concrete pipes consist of three parts: a concrete pipe core reinforced with longitudinal pre-stressed steel, a circumferential prestressed wire wound around the external surface of the pipe core wall and a protective layer. The design criteria are as follows:

(a) The pipes must possess the necessary strength and be able to resist leakage;

(b) There must be sufficient rigidity in the longitudinal direction to prevent cracks and breaking of pipes during pre-stressing, unshuttering, transport and installation;

(c) The compressive stress of the core pipe σ_c must be as follows:

Inner diameter $D_i \leq 50$ cm, σ_c = 3-8 kg/cm^2

D_i = 60-80 cm, σ_c = 3-6 kg/cm^2

D_i = 100-130 cm, σ_c = 2-3 kg/cm^2

Experience has shown that when the diameter of a pipe is less than 30 cm, the thickness of the pipe will be 2-3 cm and the length 2-3 m. When the diameter is 30-130 cm, the thickness will be 4-8 cm and the pipe length 3.2-4.2 m.

The strength of the pipe depends mainly upon the technology and workmanship during manufacture. Usually, the results of computation are merely used as a reference in the selection of the steel reinforcement bar. The actual strength of the pipe is measured by the water pressure test. The following data is used for computation (see figure 30):

D_i = Inner diameter of the pipe (cm)

r_i = Inner radius of the pipe (cm)

t = Thickness of the core pipe (cm)

L = Length of the pipe (m)

t_1 = Thickness of outer protective layer (cm)

H = Design water head (m)

p = Equivalent inner water pressure (kg/cm^2)

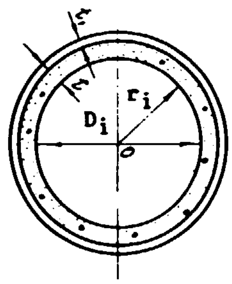
R_g = Ultimate strength of pre-stressed steel bar typically,

(R_g = 7,000-8,000 kg/cm^2)

R_a = Compressive strength of concrete

R_ℓ = Tensile strength of concrete

Figure 30. Dimensions of prestressed concrete pipe



In a circular direction, taking L = 100 cm for computation, the tensile force on the pipe wall is:

$$N = 100\ r_i p\ (kg) \qquad (36)$$

The area of the reinforcement steel bars in the pipe wall is:

$$A_g = \frac{kN}{R_g}\ (cm^2) \qquad (37)$$

where k = Coefficient of safety, 2.0

The following formula should be used in calculations for the prevention of cracking:

$$K_f N \leq A_h(R_\ell + \mu\sigma_o) + 200\ A_g \qquad (38)$$

where A_h = Cross-sectional area of pipe wall 100 cm long (cm^2)

σ_o = Effective pre-stressed force (kg/cm^2)

K_f = Safety coefficient on cracking

Fraction of steel $\mu = Ag/An$

Substitute μ, N, Ag and R_ℓ in (38) to obtain σ_o.

The loss of pre-stress is σ_5 and the total pre-stress $\sigma_k = \sigma_o + \sigma_5 \leq 0.8\ R_b$. This condition must be met; 0.8 is the coefficient of stress control.

In normal cases, when μ is not high, the loss in pre-stress lies between 1,000 and 2,000 kg/cm^2. For pre-stressed structures based on pre-tension methods, a σ_5 greater than 1,000 kg/cm^2 is recommended.

Technology and quality examination of pre-stressed concrete pipes

In order to satisfy design requirements for optimal working capability, pre-stressed concrete pipes should possess sufficient resistance to permeability and cracking as well as sufficient durability. These two qualities depend on quality control during the manufacturing process. Resistance to permeability is determined not only by material quality and mixing ratios but also by the pipe core moulding technology. The application and control of longitudinal and circumferential pre-stress on the pipe and the concrete strength of the pipe core are two factors affecting the crack resistance of the pipes. Rusting of the circumferential pre-stressed wire will reduce the durability of pipes to a considerable degree. Quality control of pre-stressed concrete pipes in a three-stage technology using the centrifugal method has therefore been fully adopted in China.

Control of longitudinal pre-stress

The longitudinal pre-stressing of pipes is achieved by pre-stretching the longitudinal steel, which is then temporarily anchored on the pipe mould before the pipe core is moulded in order to increase the level of possible pre-compressive stress after moulding. Both the electrothermal and the screw-rod stretching method are commonly used to apply longitudinal pre-stress, as shown in figures 31-33. The pre-stress value of longitudinal steel is controlled by the elongation value of steel. The steel is stretched up to the specified elongation value, which can be calculated by means of the following equation:

$$\Delta_\ell = \frac{\sigma_k + 300}{E_g} \qquad (39)$$

where Δ_ℓ = Elongation value of longitudinal steel (cm)

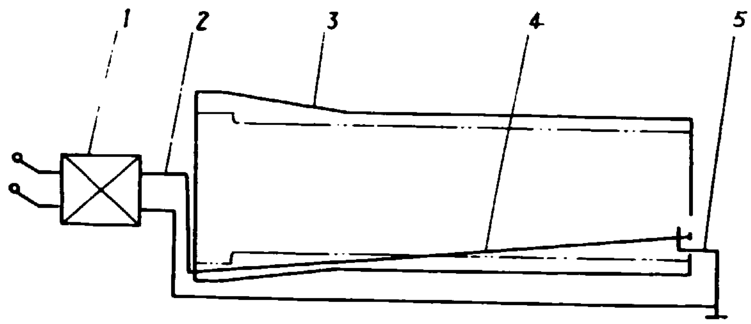
σ_k = Controlled stretching stress of longitudinal steel (kg/cm^2)

E_g = Modulus of elasticity of steel (kg/cm^2)

ℓ = Distance between two anchorage points at the ends of longitudinal steel (cm)

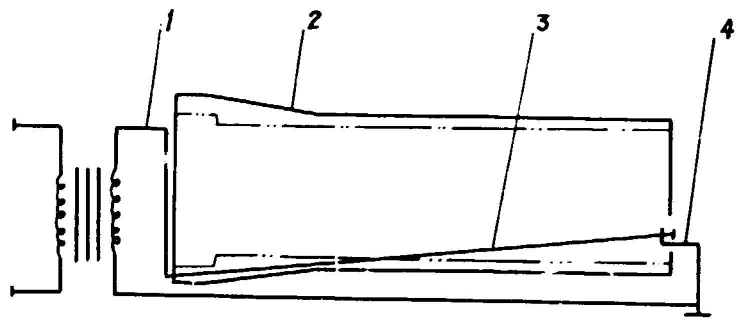
300 = Pre-stress loss caused by unevenness in the steel and plastic deformation of steel under high temperature and stress action (kg/cm^2)

Figure 31. Connection of arc-welding machine with electrothermal steel bar



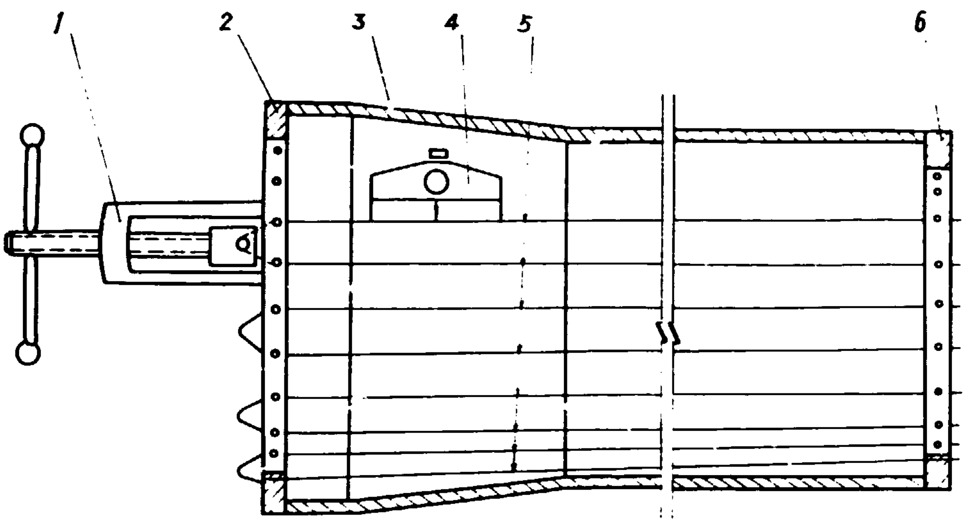
Key: 1 Arc-welding machine
2 Secondary coil lead
3 Pipe mould
4 Longitudinal steel
5 Electrothermal support bracket

Figure 32. Connection of three-phase transformer cable with steel bar



Key: 1 Secondary coil lead
2 Pipe mould
3 Longitudinal steel
4 Electrothermal support bracket

Figure 33. Stretching of longitudinal steel



Key:
1 Screw-rod stretching device
2 Socket anchorage capstan
3 Pipe mould
4 Wire tensiometer
5 Longitudinal prestressed steel
6 Spigot anchorage capstan

A wire tensiometer is used to measure the pre-stress value of the longitudinal steel.

Quality control of aggregates

The quality requirements of sand and stone for pre-stressed concrete pipe are generally the same as those for high-grade concrete. However, clay impurities and stone power in the sand must be completely eliminated for the concrete to possess sufficient resistance to permeability.

Control of concrete mixing ratios

Before mixing, the proportion of concrete used for pipe manufacture should be determined by testing and not randomly changed, otherwise the permeability-resistant property will fluctuate. The control of concrete mixing ratios is primarily designed strictly to control the water-cement ratio in concrete after using the centrifugal moulding method. The remaining water-cement ratio is generally 0.66-0.68 times the water-cement ratio before the centrifugal moulding operation. In other words, the water-cement ratio in concrete before centrifugal processng is proportional to the remaining water-cement ratio in concrete after centrifugal moulding. The arbitrary addition of more water must therefore be forbidden.

Three-stage control of the centrifugal process

Control of centrifugal technology involves speed and time adjustments in the slow-, intermediate- and high-speed stages of centrifugal technology.

Slow-speed rotation is the first step in centrifugal technology, the im of which is to facilitate material feeding and to make concrete materials uniformly adhere more firmly to the pipe mould wall. For this purpose, the centrifugal force produced by the rotating speed should be larger than the deadweight of the concrete material, that is:

$$m\, w^2 r > mg \qquad (40)$$

where m = Mass of concrete (g)

w = Angular velocity = $2\pi n/60(s^{-1})$

r = Rotating radius, namely, the external radius of the pipe core (cm)

g = Acceleration of gravity = 981 cm/s^{-2}

n = Rotating speed of pipe mould (rev/min)

The following expression for slow speed is therefore obtained:

$$n > \frac{300}{\sqrt{r}}$$

In practice, the controlled slow speed is generally taken as 1.5 or 1.6 times n.

The slow-speed centrifuge depends upon the degree of uniformity of the material distribution on the pipe mould wall. It will be longer for pipes with a larger diameter and shorter for ones with a smaller diameter. In general, it takes 5-15 minutes.

Figure 34 shows the feeding process in pipe core centrifugal moulding.

Intermediate-speed rotation forms the transitional stage from low- to high-speed rotation. This transitional speed should be uniformly increased. Due to the relatively low water-cement ratio in concrete used in centrifugal technology, the flowability of the concrete mixture is relatively small. Abruptly increasing the rotation to a high speed will result in displacement of material and cause non-uniformity in the thickness of the pipe wall. In addition, an abrupt rise in speed will cause skipping in the pipe mould, thus intensifying the separation of material. The principle of intermediate speed control is therefore gently to raise the speed from low to high. The revolutions per minute and the length of time required should be determined by practical observation. In general, the length of time is normally never more than 10 minutes.

High-speed rotation is the final stage in centrifugal technology, at which the concrete achieves its maximum density. The centrifugal pressure may be expressed as follows:

$$P = \frac{\gamma_h \pi^2 n^2}{2,700g}\left(r^2 - \frac{r_i^3}{r}\right) \qquad (41)$$

where F = Centrifugal pressure of core concrete acting on pipe mould (kg/cm^2)

γ_h = Unit weight of concrete (kg/cm^3)

n = rotation speed of pipe mould (rpm)

r_i, r = Internal radius and external radius of the pipe respectively (cm)

It may be shown from equation 41 that when the dimensions of the pipes are constant, the larger the rotation speed, the larger will be the centrifugal compressive force. Hence, raising the centrifugal rotation speed is an important means of increasing the strength and permeability resistance of the pipes.

Figure 34. Pipe core feeding process

In high-speed centrifugal technology a rotation speed corresponding to a centrifugal compressive stress of 0.8-1.0 kg/cm^2 is considered best. However, the best rotation speed is hardly ever attained because of the poor rigidity of the pipe mould which has usually been made by a hand manual with a steel plate 3-6 mm in thickness. The centrifugal pressure which the pipe mould can withstand does not always exceed 0.5 kg/cm^2. Based on production practice, when a pre-stressed concrete pipe with an internal diameter of 125 cm is manufactured, a centrifugal pressure of 0.73-0.75 kg/cm^2 is needed to enable the permeability resistance of the pipe to reach 34 kg/cm^2 or above. It can then safely be used in a high-head hydropower plant with a design internal water pressure of 21.2 kg/cm^2. Control of high-speed centrifugation should therefore be determined according to the diameter of the pipe and the magnitude of the perm ability-resistant pressure required. Generally speaking, centrifugal pressure acting upon the pipe mould should be in the range of 0.4-0.75 kg/cm^2. The higher or lower limit is required for, respectively, high or low permeability-resistant pressure.

The time needed for high-speed centrifugation is determined by the degree of drainage, the density of concrete and sometimes by the water pressure test.

Since segregation results from the centrifugal process, the impermeability of the concrete pipe core mainly depends upon the mortar layer and the cement layer. Together they are called the permeability preventive layer, the thickness of which is only one fourth of the entire pipe thickness. If a method is used whereby both feed and centrifugal processes are done layer by layer so that multiple permeability preventive layers are formed on the pipe wall, the permeability resistance will be markedly increased. Generally, the feed-and-centrifuge process can be repeated up to four times, depending on the desired thickness of the pipe wall and the diameter of the pipe.

Control of the circumferential prestress

The circumferential pre-stress wire is wound around the external surface of the pipe core wall. A weight-balanced tension-type wire-winding machine is extensively used to wind circumferential pre-stressed wire (see figures 35 and 36). The wire is subjected to a tension equaling one half of the weight of the weight block. The pre-stress value of the circumferential wire may be controlled by adjusting the weight of the hung weight block and calculated by means of the following equation:

$$W = 2\sigma_k f_y \qquad (42)$$

where W = Weight of the weight block (kg)

σ_k = Controlled tensile stress of circumferential wire (kg/cm^2)

f_y = Cross-sectional area of a single circumferential wire (cm^2)

The circumferential pre-stressed wire is wound onto the pipe core through the guide pulley mounted on the gantry, which moves forward when the pipe core rotates. The pitch of the wire to be wound may be controlled by adjusting the moving velocity of the gantry.

If circumferential hair cracks appear on the internal surface of the pipe core wall after wire winding, it is necessary to examine whether the structural design of the pipe is reasonable, whether pre-stress on the longitudinal steel was sufficiently applied during the pipe-manufacturing process, and whether the pipe core reached its specified strength during the wire-winding operation. Appropriate measures should then be taken for improvement, for example through the use of epoxy resin for repairs.

Figure 35. Prestressed steel bar wound on the pipe core

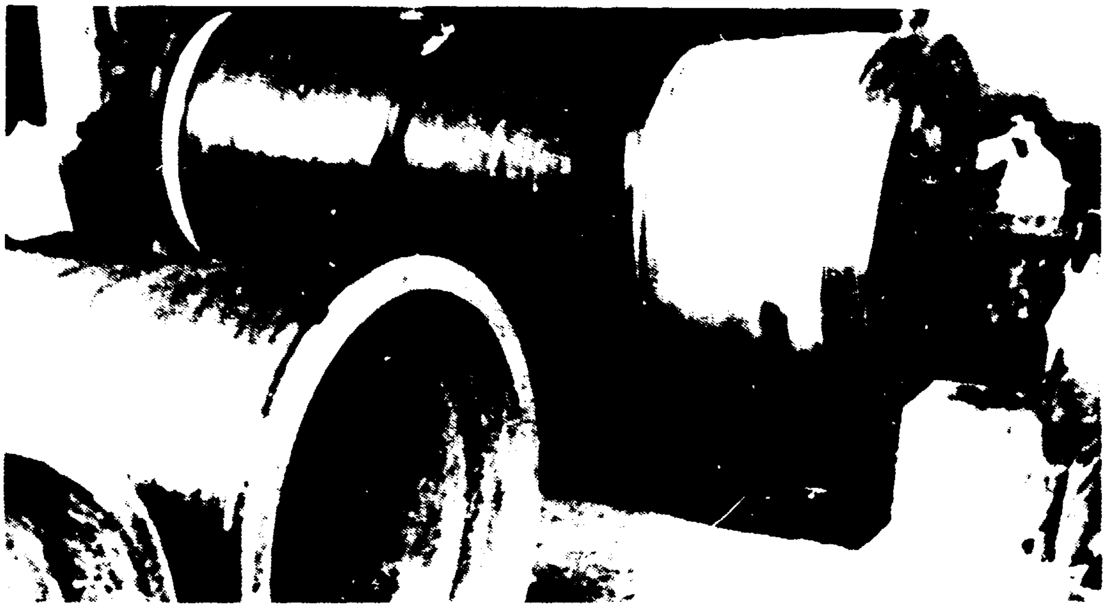
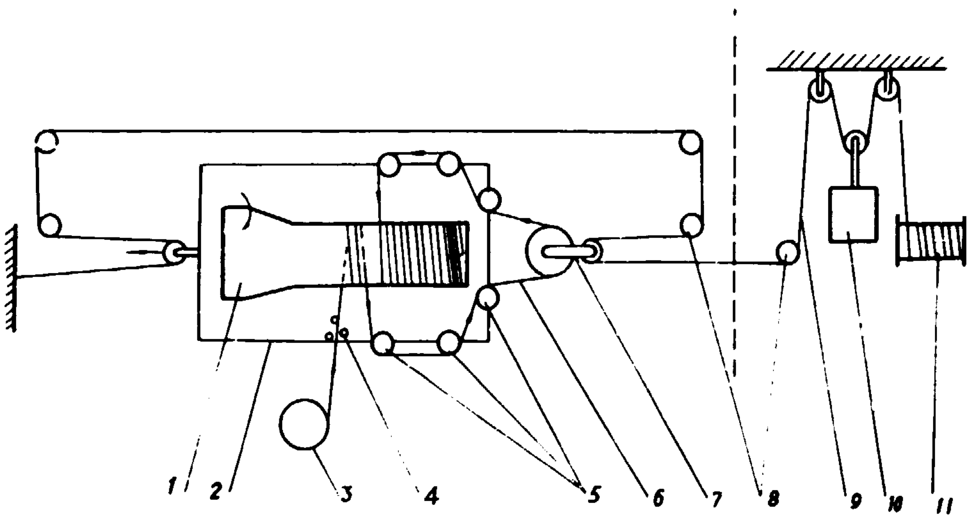


Figure 36. Weight-balanced tension-type wire-winding machine



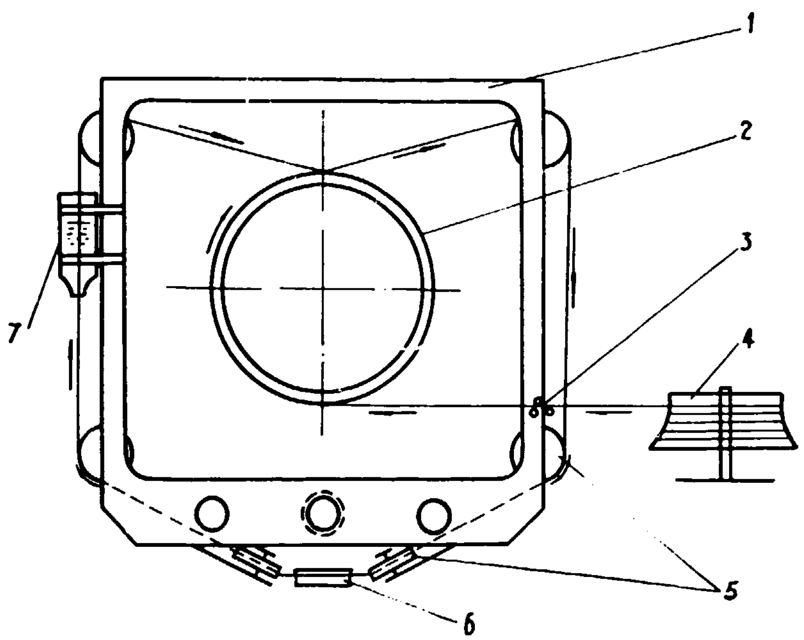
Wire-winding system | Balancing weight system

Key:
1 Pipe core
2 Gantry
3 Steel wire capstan
4 Wire-fastening and guide device
5 Prestressed-wire guide pulley
6 Prestresse' wire
7 Tension-transmitting device
8 Steel-cable guide pulley
9 Steel cable
10 Weight block
11 Winch

Protection of circumferential pre-stressed wire

The service life of pre-stressed concrete pipe is rather long, but the circumferential pre-stressed wire can break due to rust erosion and cause failure of the pipe. In general, a cement mortar layer 15-20 mm in thickness is mechanically or manually made on the pipe surface as a protective coating. A method currently used to protect circumferential pre-stressed wire is to apply a rust-preventive coating on the wire. The most practical method is to install a container of rust-preventive material on one side of the gantry in the wire-winding machine as shown in figure 37. When the wire passes through the container, a rust-preventive coating is automatically applied to its surface just before it winds onto the pipe core. Then, if the cement mortar protective coating fails, the rust-preventive coating will still remain on the steel wire itself.

Figure 37. Automatic application of rust-preventive coating on prestressed wire



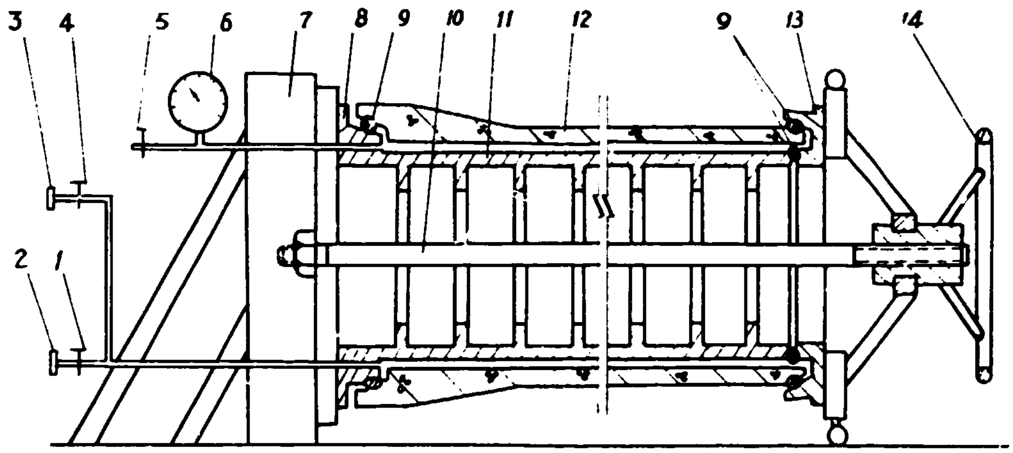
Key:

1 Gantry
2 Pipe core
3 Wire-fastening and guide device
4 Steel wire capstan
5 Steel-wire guide pulley
6 Tension-transmitting device
7 Rust-preventive container

Hydraulic pressure test

Permeability resistance and crack resistance can be determined by using a hydraulic pressure test. The equipment used in conducting hydraulic pressure tests is a water-filled type of hydraulic pressure testing machine. For larger-diameter pipes that will be subjected to higher pressure, an internal-sleeve-type hydraulic pressure testing machine, as shown in figure 38, may be more convenient. The latter type can greatly reduce the total thrust of water pressure against the bulkhead at both pipe ends, making water sealing between the bulkhead and the pipe easier to carry out.

Figure 38. Internal-sleeve-type hydraulic pressure testing machine



<u>Key</u>:
1 Water intake valve for pressure test
2 Connection to electrical pressure test pump
3 Connection to water pump
4 Water-filling valve
5 Air release valve
6 Pressure gauge
7 Machine support
8 Stationary bulkhead
9 Water-sealing rubber ring
10 Tension rod
11 Steel sleeve
12 Prestressed concrete
13 Movable bulkhead
14 Hand wheel

Since pre-stressed concrete pipes used in hydropower stations are always laid along a hill slope in the open air and are not subjected to earth pressure and other live loads acting on the ground surface, the pressure used in hydraulic examinations is always taken as 1.3 times the sum of the hydrostatic pressure and water-hammer pressure increment, that is, 1.3 times the designed internal water pressure. If percolation and cracks do not appear in the pipe under such water pressure conditions, the pipes may be considered acceptable. All pipes should be installed and employed only after passing both the permeability resistance and the crack resistance test.

More than ten years of usage have shown that pre-stressed concrete pipes possess higher crack resistance and better permeability resistance. It has been verified that use of this type of pipe in hydroelectric stations under 200 m of water head is both feasible and safe. Pre-stressed concrete pipes with a diameter of less than 1,300 mm can be manufactured with comparatively simple equipment on site or in the plant.

Use of relief valves

If the load of a hydropower unit is rejected suddenly during operation, the governor will automatically cause the turbine quickly to close its guide vanes, consequently producing the penstock pressure rise ξ and the turbine speed rise β · ξ and β can be both expressed as functions of the principal variable T_s, the closing time of the guide vanes. It is known from the characteristics of the penstock and the turbine that ξ will vary contrary to β for a certain range of variation of T_s. That is, when T_s increases, ξ will decrease while β increases, and vice versa. For a hydropower station with short penstock (normally the starting time of penstock T_w is less than 2.5 seconds) reasonable values of ξ and β can be obtained if T_s is properly selected. For a hydropower station with long penstock, however, it is often impossible to select an appropriate value of T_s that will make both ξ maximum and β maximum fall within an allowable range. In such a case, a surge shaft or surge tank is usually installed to achieve acceptable values of ξ maximum and β maximum, thereby ensuring stability of the regulation system. Such an arrangement shortens the effective length of the penstock and reduces the value of T_w within allowable limits. However, using surge shafts requires larger amounts of building materials, higher construction costs and an increase in the time needed for construction. Moreover, for some sites, surge shafts are difficult to construct owing to poor topographical and geological conditions. In order to reduce capital investment and speed up construction, a scheme of replacing the surge shaft with a relief valve employing a novel all-oil control system was developed. Tests conducted on a single relief valve at one hydropower station, and further industrial tests and four years of operating experience at another, have shown that the application of type TFW-400 relief valves with an all-oil control system can successfully replace a surge shaft.

In the above-mentioned scheme, the total length of tunnel plus penstock was 1,950 m, the head 83 m and the unit capacity 1,600 kW. In the case of a rejection of the full load in all three units, the penstock pressure rise ξ is 14.5 per cent and the turbine speed rise 24.4 per cent. These values are appreciably lower than those for a design with a surge shaft (ξ = 24 per cent, β = 32 per cent) and very close to the optimum values ξ = 11.2 per cent and β = 25.5 per cent. The transient stability under conditions of no-load and on-load disturbance for the turbine regulating system also meets the requirements of the power station. A saving of 90 per cent of the cost of a surge shaft was realized in addition to the power station's being put into commission one year ahead of schedule.

Type TFW-400 relief valve with all-oil control system

The action of the relief valve must be sensitive, safe and reliable when used in place of a surge shaft in hydropower projects. Most relief valves used in the past were of the mechanical type. Experience has shown them to be unreliable, and the action of relief valves also lags behind that of guide vanes by up to 0.5 seconds. Consequently, even if a relief valve is installed in a hydropower station, the penstock pressure rise will still be very high. Special safety measures would have to be taken to protect the penstock in case of relief valve failure. Mechanically controlled relief valves could not therefore completely take over the function of reducing the water hammer. Various designs of relief valves with hydraulic control systems were somewhat improved but shortcomings were still quite evident. For example, some valves still retained a time lag of 0.1-0.4 seconds; some valves required an increase in the capacity of turbine pressure oil systems; and others had complicated systems comprising large numbers of control elements that were difficult to adjust on site. The above-mentioned shortcomings have all been overcome in the type TFW-400 relief valve. The valve proper and control system are described below.

The type TFW relief valve (see figure 39) is of a horizontal arrangement. The main servomotor and pilot oil chamber are integrally connected with the valve casing, thus ensuring a simple construction and compact arrangement.

The cast-steel valve casing is made up of two partially spiral-shaped ducts symmetrical to the vertical centre line. Stay vanes in the valve casing will turn the incoming water into vortex flow, thus achieving effective energy dissipation before the water is discharged into the tail-race. The valve is equipped with an air supply device to reduce vibration during operation.

The valve plug, which may be conical or round, is made of cast steel with surfaces plated with chromium for rust prevention. Several balancing holes are provided on the valve plug to reduce operating pressure.

Sealing of the valve is ensured by the close contact between the stainless-steel overlaid seal ring on the valve plug and the removable phosphorous-bronze seal ring on the valve body. These two surfaces are precisely ground and fitted to give satisfactory sealing.

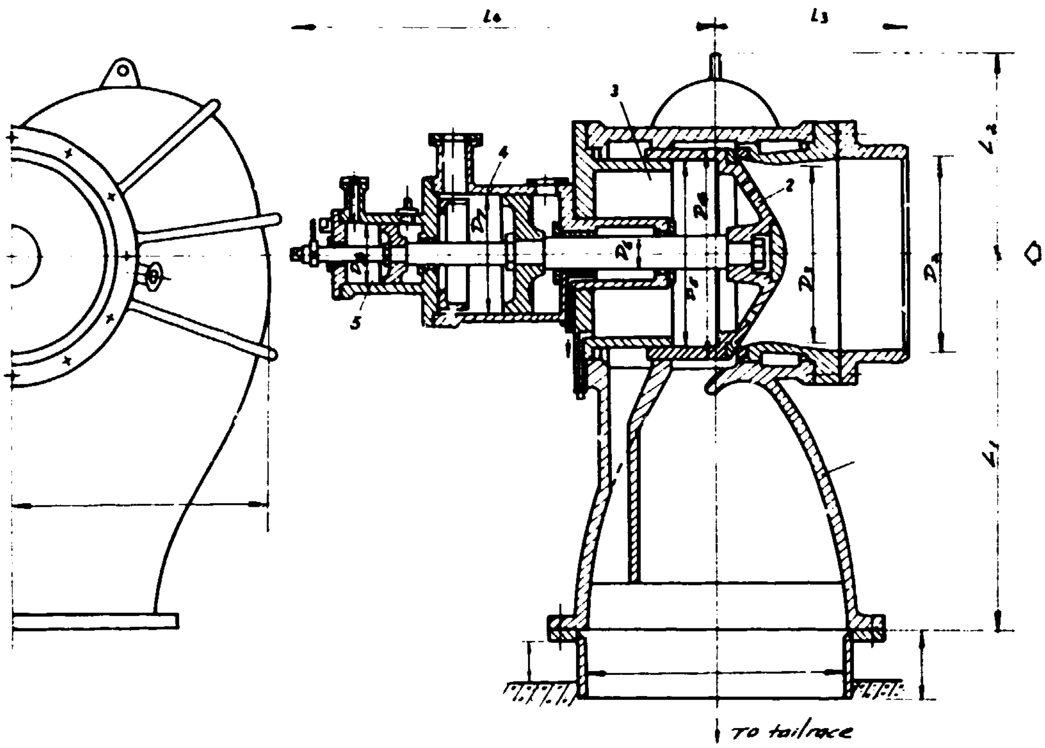
The main feature of the relief valve control system (see figure 40) is the employment of pressure oil for direct and complete control and operation. It also has a two-step closing device for the guide vanes.

The action of the control system is outlined below:

(a) When the turbine load is constant, the piston of the main distributor is at the middle position and the oil under pressure flows into the closing chamber of the relief valve via a throttle hole, while the opening chamber is connected to the drain. Because the oil pressure in the closing chamber of the main servomotor is higher than the water thrust on the valve disc, the relief valve remains in a closed position;

(b) When the turbine load is reduced by a small amount (within 15 per cent of the rated output), the main distributor only moves upward a small distance, so that a limited amount of oil under pressure enters the closing chamber of the main servomotor to make the guide vanes close slowly, while the relief valve remains closed;

Figure 39. Structure of pressure relief valve



Key:
1 Valve casing
2 Valve disc
3 Balancing chamber
4 Main servomotor
5 Pilot oil chamber

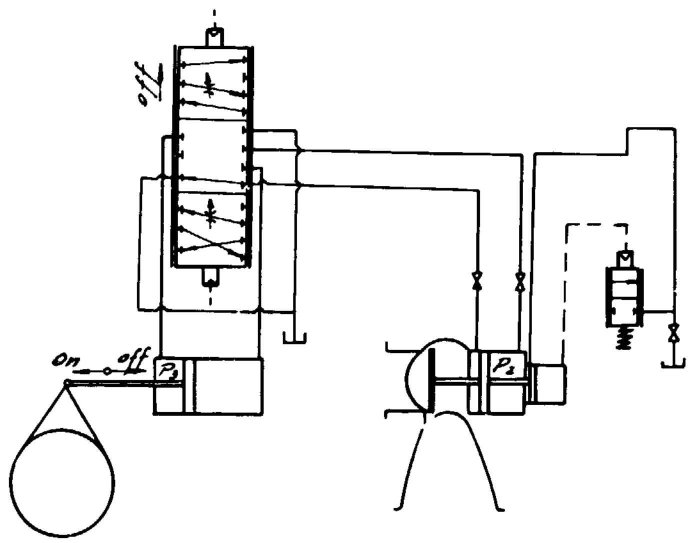
(c) When more load is rejected momentarily (greater than 15 per cent of rated output), the upward ι tion of the main distributor piston is much larger and the relief valve opens quickly at the same time as the guide vanes close. The action of the two is synchronized with a zero time lag;

(d) As the turbine load increases, the oil under pressure ρ flows directly into the opening chamber of the main servomotor. The relief valve remains at the closing position;

(e) The stepped closure device is thrown in when the relief valve starts to open fast. The relief valve accelerates to the position determined by the limiting ring and then proceeds at a lower speed, thus causing the guide va es to close in two stages. The breakpoint of the two-step device can be easily adjusted on site.

Should the relief valve fail to work, the guide vanes have to be closed slowly to ensure that the penstock pressure rise will not exceed allowable limits.

Figure 40. Relief valve control system



Stability and transient process quality of the turbine regulating system

When using the relief valve, the following problems are of great importance: calculation of the maximum penstock pressure rise ξ and the maximum turbine speed rise β when the load is rejected; and calculation of the transient stability of the turbine regulating system when small disturbances occur.

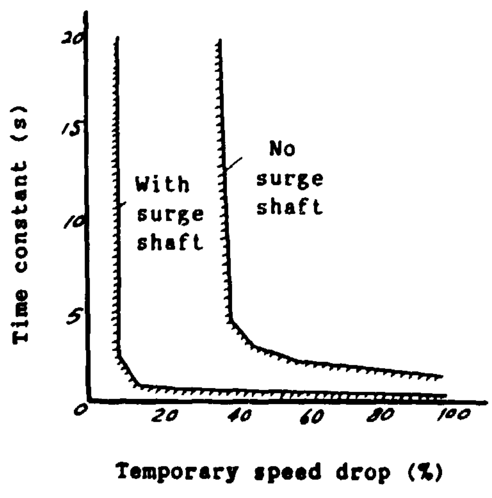
For many years the practice has been to compute the two aspects of the same problem separately. That is, in the case of load rejection, formulas such as the Allievi formula were used for the calculation of the maximum penstock pressure rise ξ and the S.M.S. formula for that of the maximum turbine speed rise β. In the case of small load disturbances, the stability and transient quality calculations were carried out by simplifying the original high order regulating system to a third-order system consisting of an ideal turbine, and ideal governor and a rigid-column water hammer. Obviously, such a method of calculation will not be suitable in cases of hydroelectric stations with a long penstock and a relief valve.

The present study treats the transient stability of the regulating system on the basis of modern control theory and integrates the calculation for large and small perturbations. It takes into account the non-linearity of the turbine elements and some important non-linear factors of the governor, such as the saturation characteristic of the frequency measurement device, the stroke limit of the dashpot, and the dead band and stroke limit of the main distributor and servomotor. Accurate results on both regulation guarantee and stability, as well as transient quality calculation, may be obtained simultaneously.

The computation has been presented in the paper entitled "Application of relief valves in small hydroelectric stations", prepared for "The Second Seminar Workshop of Transfer of Technology on MHG", organized by UNIDO in 1980.

Figure 41 compares the relative stability of a relief valve and a surge shaft for a unit equipped with a type XT-600 governor (mechanical type) when operating separately.

Figure 41. Comparison of stability region of governor



The units run smoothly when they are connected to a large network, but when each unit carries an isolated load, the stability under small perturbations mainly depends upon the performance of the governor, because the larger the penstock, the higher the performance demand on the governor. Therefore, when making the choice to use relief valves instead of a surge shaft, - phasis should be put on the technical requirements of the governor according to the actual conditions of a given hydropower station.

Serial design of the relief valve and its application

The initial three sets of TFW-400 relief valves with all-oil control systems were successfully put into operation early in 1976 at Longyuan hydropower station, Hunan Province.

Serial design of the relief valve for turbines of different type are under way. Seven models for various head ranges with four diameters (ϕ 400, ϕ 600, ϕ 800 and ϕ 1,000 mm) have been designed and manufactured. The main data is shown in table 24.

The range of application of the various relief valves is shown in figure 42.

Figure 42. Range of application of pressure relief valves

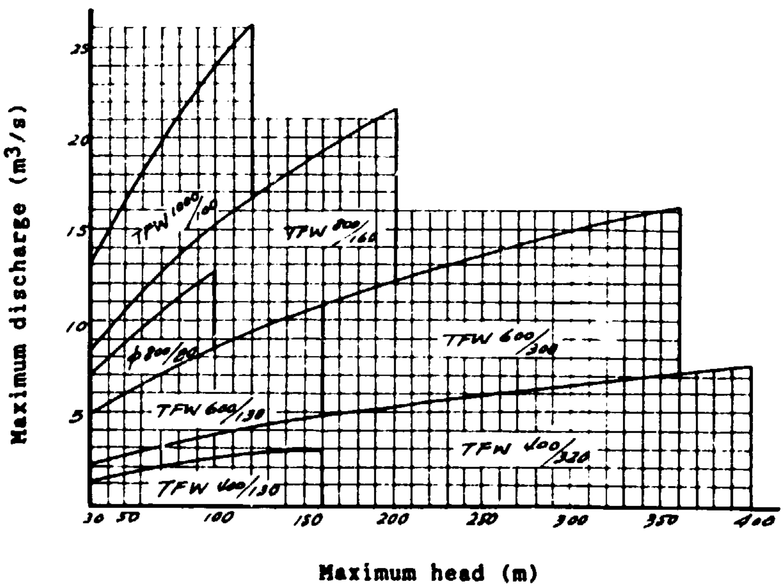


Table 24. Main features of TFW relief valves

Item	TFW 400/130	TFW 400/320	TFW 600/130	TFW 600/300	TFW 800/80	TFW 800/160	TWF 1 000/100
Diameter D_x (mm)	400	400	600	600	800	800	1 000
Maximum stroke Y_x (mm)	80	100	150	150	200	200	250
Nominal head H_p (m)	130	320	130	300	80	160	100
Maximum head $H_{max} = (1 + \ \ ) H_p$ (m)	160	400	160	360	100	200	120
Maximum discharge Q_x (corresponding to H_{max}) (m^3/s)	3.15	7.67	10.9	16.4	12.8	21.7	26.3
Weight of valve (tonnes)	1.2				5	8.5	

Relief valves in place of surge shafts have been used in more and more projects and stations after the successful experiences at the Longyuan hydropower station.

Investment savings of more than ¥RMB 5.4 million have been achieved as a result. The above savings do not include cases where topographical and geological conditions have not permitted the construction of a surge shaft. Investment savings in these cases are difficult to evaluate precisely.

The following conclusions may be drawn from the foregoing analysis:

(a) The relief value with all-oil control systems exhibits advantages in sensitivity (no time lag), safety and reliability, simplicity in structure, convenience in adjustment and maintenance. A hydraulic interlock is built between the relief valve servomotor and the turbine servomotor to allow accurate synchronization. With added safety to the penstock and the turbine thus ensured, the stepped-closure device permits the selection of better parameters of regulation. Values of ξ and β can be determined from two independent time constants, that is, the value of ξ from the turbine slow closing time and the value of β from the fast closing time T_m;

(b) The relief valve with all-oil control systems will not act in case of small perturbations. When selecting governors for a hydropower station equipped with relief valves, the governor temporary speed drop b_t, the time constant of the damping device T_d and other related parameters should have the largest range of adjustment possible;

(c) Because of the difference between the flow characteristic of the turbine and of the relief valve, a perfect match is difficult, with the result that a pressure depresssion often takes place at the beginning and end intervals of guide vane closing. Uniform variation of flow in the whole penstock system can be attained by rational selection of opening and closing intervals of the relief valve and guide vanes. Pressure depression can thus be retarded or avoided.

B. Technical innovation

Water resistor device

A water resistor device may be used in place of a surge shaft. Successful results have been obtained by some hydropower stations using a pressure relief valve instead of a surge shaft, although it involves certain limitations. A pressure relief valve is applicable only to medium or small hydropower stations with a medium or high head. A plant with a low head and a big flow would require an oversized valve and involve complications in manufacture, high cost of outlet structure etc. It is also unsuitable to use the pressure relief valve in stations where the silt content of the water is high.

In 1962, a water resistor device was first used at the Wang Jia Chang power station (installed capacity 3 x 1,360 kW), Hunan Province, to replace the surge shaft in order to overcome the difficulty of building a surge shaft at the foot of the dam. The total cost in building the water resistor device was ¥RMB 30,000 while the cost of building a surge shaft in the original design would have been ¥RMB 110,000. Since then, the water resistor device has been recommended for use in other power stations in China and further improvements have been made.

This device is similar in principle to the load balance. Calculations should be made of the rise in pressure and speed if the load is suddenly rejected to see whether to use a water resistor device or not in a hydropower station. The water resistor device should be applied only when the calculating value exceeds the allowable value stipulated by technical regulations.

When the load is suddenly rejected and the active capacity in the generator stator simultaneously disappears, the water resistor should be put into operation at that moment by the starting elements as a dummy load. The speed governor would therefore not be shut down, the guide vane would shut only a little and transition processes with little fluctuation would be produced in the pressure penstock and the unit. When the unit is stabilized after loading up the water resistor, it can be unloaded gradually and the unit shut down. By this operation, the pressure and speed rise can be guaranteed within the permissible range stipulated by the regulations.

If the loading-up of the water resistor and the disappearance of the active capacity in the generator stator happens at the same time, the value of pressure and turning speed will not be raised. In fact, because of the impossibility of synchronism in operation of the starting elements, the loading-up of the water resistor always lags behind the disappearance of the active capacity in the generator. When the time lag between the loading-up of the water resistor and the disappearance of the active capacity in the generator lengthens, the effectiveness of reducing the pressure and the rise in turning speed will be decreased. On the contrary, the sooner the water resistor is loaded up, the more obvious the effectiveness will be. The starting elements for the device should therefore possess high sensitivity.

An analysis of operations in hydropower stations, shows that accidents might have happened in the generator or in the water resistor when the latter was put into operation. It is therefore assumed in the design criteria that one unit is suddenly unloading entirely and not loading up the water resistor. In that case, it should be guaranteed that the value of pressure and the rise in turning speed do not exceed the permitted values.

It is rare that inner accidents happen to both units at the same time. In such an emergency, the rise in pressure is permitted to exceed the allowable value but is limited by the pressure value at which the penstock will be destroyed (the prolongation of the closing time T_s could also be adopted).

In order to prevent the rejection of the water resistor, a spare-water resistor device should be installed, but special attention must be paid to its maintenance and repair during the operation.

Experiments carried out in three hydropower stations showed that the water resistor can take the place of a surge shaft in operation, and that the effectiveness of the water resistor is affected by the time lag in putting it into operation.

Third harmonic voltage excitation system

The manufacture and testing of the third harmonic voltage excitation system was started during the 1960s in China. At present, there are two categories of third harmonic voltage excitation in China. One is for a unit of less than 500 kW in capacity, which generally uses single-phase harmonic winding in providing exciting current to the magnetic field of the generator through non-controlled silicon rectifiers. Though simple in structure and cheap in cost, it has the shortcoming of being unstable in parallel operations and therefore has not been often used. The other category is for generator sets greater than 500 kW, all of which use SCR as the rectifying component. Types of harmonic winding include a three-phase and a single-phase winding integrated with a fundamental wave winding. In China, there are three provinces where success has been achieved in trials with this type of excitation. Three types of generator with a capacity of 1,250, 630 and 800 kW, respectively, have been built and erected in several stations and operated for 5-8 years with good stability, not only in isolated operation but also in various forms of parallel operation.

One of the advantages of the third harmonic voltage excitation system is its economic viability. In a 630 kW generator, type TSW 143/39-12 (with T indicating synchronous generator, S hydro, W horizontal, 143/39 diameter and length of stator laminated sheet in centimetres and 12 the number of poles), the excitation facility originally used was a d.c. exciter and an old compound excitation regulator. Later, the magnetic poles of the motor were modified and a set of additional third harmonic winding was added to the slot of the stator with the stator sheet diameter unchanged. A set of specially designed SCR and an automatic regulator was fitted to the generator. The cost of the new excitation system is 87 per cent of the older system, and if only the cost of the excitation system is accounted for (with generator proper excluded), the new type is only 58 per cent of the older one. Moreover, the harmonic voltage excitation saves about 50 per cent in the amount of copper used in the system. Even compared with the generally used SCR excitation, which operates with a transformer at an outside terminal of the generator, the harmonic voltage excitation can produce savings in both cost and copper.

In addition to having the advantages of SCR excitation, harmonic voltage excitation has other excellent features, such as the ability for self-sustained functioning and the very little influence on it of frequency fluctuations.

Another benefit to smaller stations is that harmonic voltage excitation requires less maintenance and repair work in comparison with the d.c. exciter, which often requires mechanical processing in dealing with the commutator erosion.

Nevertheless, the design and theory of this type of excitation continue to pose challenging problems which China is seeking to resolve.

<u>Guaranteeing quality and increasing the reliability of the power supply</u>

MHG stations with a unit capacity larger than 500 kW are usually equipped with an automatic governor control and a voltage regulator. Under normal conditions, both the voltage and the cycle would be kept within the allowable range. For stations with a unit capacity less than 500 kW, the governor is controlled manually and the excitation system is either hand-controlled or automatic. If the station operates independently, the fluctuation range of the cycle and the voltage can be large. In local grids, the allowed fluctuation range of the cycle is from +1 Hz to -1 Hz, and that of the voltage is from +5 per cent to -10 per cent.

Following the rapid development of MHG stations, small power networks have arisen in many places, helping to improve the reliability of the power supply. Usually, the installed capacity of a grid on a county level ranges from several thousand to ten or twenty thousand kilowatts. The experience of many counties may be summarized as follows:

(a) In order to improve the reliability of power supply, the establishment of a small local grid is necessary. Integration of a small local grid with the national grid is advisable if the necessary conditions are satisfied;

(b) The small local grid must be equipped with several big units in order to bear the heaviest load and to stabilize the running of the grid;

(c) The small local grid must have a sufficient installed capacity and enough spare capacity;

(d) The task of each power station in the grid must be reasonably allocated by strengthening the dispatch work;

(e) The structure of the network should be improved to raise the quality of the transmission lines;

(f) Relay protection may be improved by dividing it into three grades, or county, commune and production brigades, in order to minimize the area possibly affected by accidents;

(g) In order to improve communications, all power stations without feeding lines with a voltage of 35 kV may be equipped with communication equipment connected with the county dispatching room.

C. Personnel training

There are various channels for technical training of MHG personnel, including institutions of higher learning, extramural courses and on-the-job training.

A number of colleges and universities in China have departments which specialize in the field of water resources and hydropower. Various engineering faculties are also concerned with hydropower. Graduates of these institutions usually become the high-level technical forces in hydropower exploration, design, construction, installation and research.

Secondary technical schools are usually established by the province or municipality and are widely spread out in areas where water resources are abundant. Graduates from secondary technical schools are usually sent to the Division of Water Conservation in the province, prefecture or county. They are the main workforce in MHG stations at the county level.

Technical schools for workers are available to train skilled workers in the field of hydropower construction, installation, operation and maintenance.

Extramural training courses are on different levels. Usually, the state-level course is sponsored by the Ministry of Water Conservation and the participants are nominated by the province. In most cases the trainees form the main workforce of the province. The training courses sponsored by the province are attended by skilled technicians who work in the county water conservation section. These courses are periodically organized according to the demand.

New MHG plants in China sometimes send their workers to old plants for training through practice. After training, the workers are sent back to the new MHG and work as apprentices.

5. Reduction of costs

The steps taken to reduce the cost of MHG in China include the following: sound planning and site selection; reasonable selection of the type of exploitation and project layout; multi-purpose utilization; serialization, standardization and popularization of machines and equipment; adoption of the results of research and development of pre-stressed concrete pipes, pressure relief valves etc.; and good design of electrical schemes and network structures and proper voltage selection. The use of local materials and dam types of simple construction are also effective means of reducing MHG costs.

The dam is the main structure used to obtain the water head in the dam-type hydropower plant. Dams are also erected in the diversion-type hydropower plant, but their main function is to improve the intake conditions.

Dams built in MHG projects in China are usually of the overflow type designed to discharge the flood in order to save the structures for flood release. They have a height of less than 5-6 m. Some of the dams built using local material are described below.

Earth dams

Earth dams are the most popular dam types in China. They can be built using local material and simple machinery. If the dam material is available, earth dams are adaptable to almost all kinds of foundations.

In the construction of earth dams, different kinds of embankment material have been used, such as loess, alluvial clay, gravelly cohesive soil and sand and gravel. In provinces with humid and rainy climates in southern China, lateritic soil has also been frequently used. Such soil, which has a high fraction of clay particles, is usually used as the impervious core of the earth dam. Figure 43 illustrates different types of earth dam.

In regions where sand and gravel are insufficient but cohesive soil is abundant, homogeneous dams have been built in an overwhelming majority. The homogeneous earth dam, simpler in construction and able to be compacted by tamping equipment, has been widely adopted in China, especially in regions where there are deep deposits of gravelly cohesive soild and loess. Homogeneous earth dams represent 65 per cent of the earth dams completed.

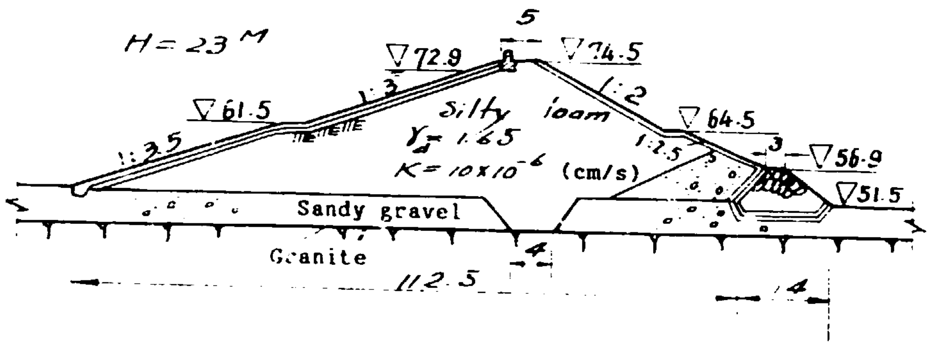
Stone masonry dam

Stone masonry dams require 40-50 per cent less cement than concrete dams and also less timber. They can be built with simpler equipment which is easy to operate. In comparison with earth dams and composite dams, the stone masonry dam is better for dealing with the flood either during construction or when in operation. A stone masonry dam can even be overflooded during the construction period. Such dams usually have a large number of effective working days per year.

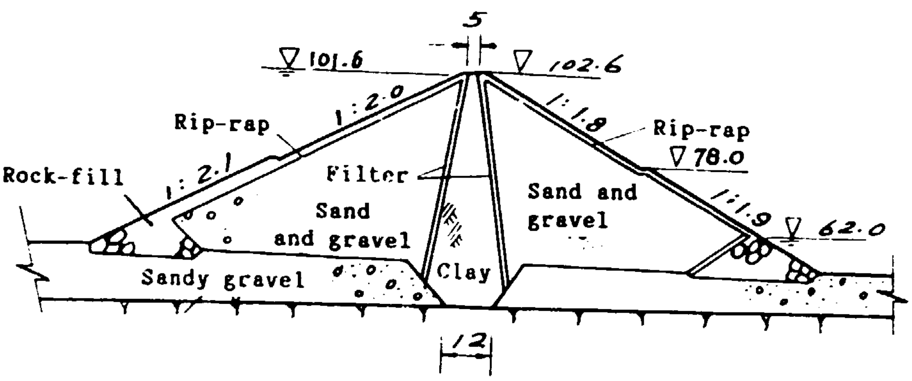
The number of stone masonry dams built in China is less than that of earth dams. In Hunan Province nearly seventy MHG plants with a total installed capacity of 413.5 MW (approximately 60 per cent of the total installed capacity of MHG in Hunan Province) have stone masonry dams, 60 per cent of which are gravity dams.

Figure 44 shows a cross-section of the Yanwotan masonry hollow gravity dam, Hunan Province. The geological conditions are favourable; there are rock outcrops on both abutments. The depth of sand and gravel deposits is

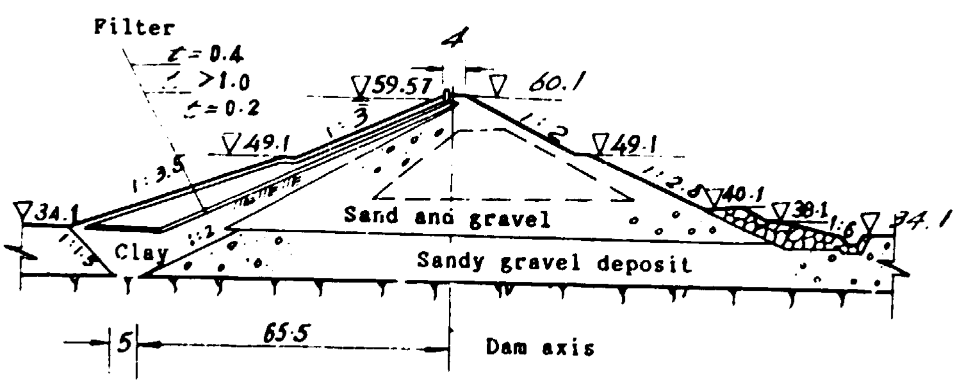
Figure 43. Types of earth dam



(a) Homogeneous

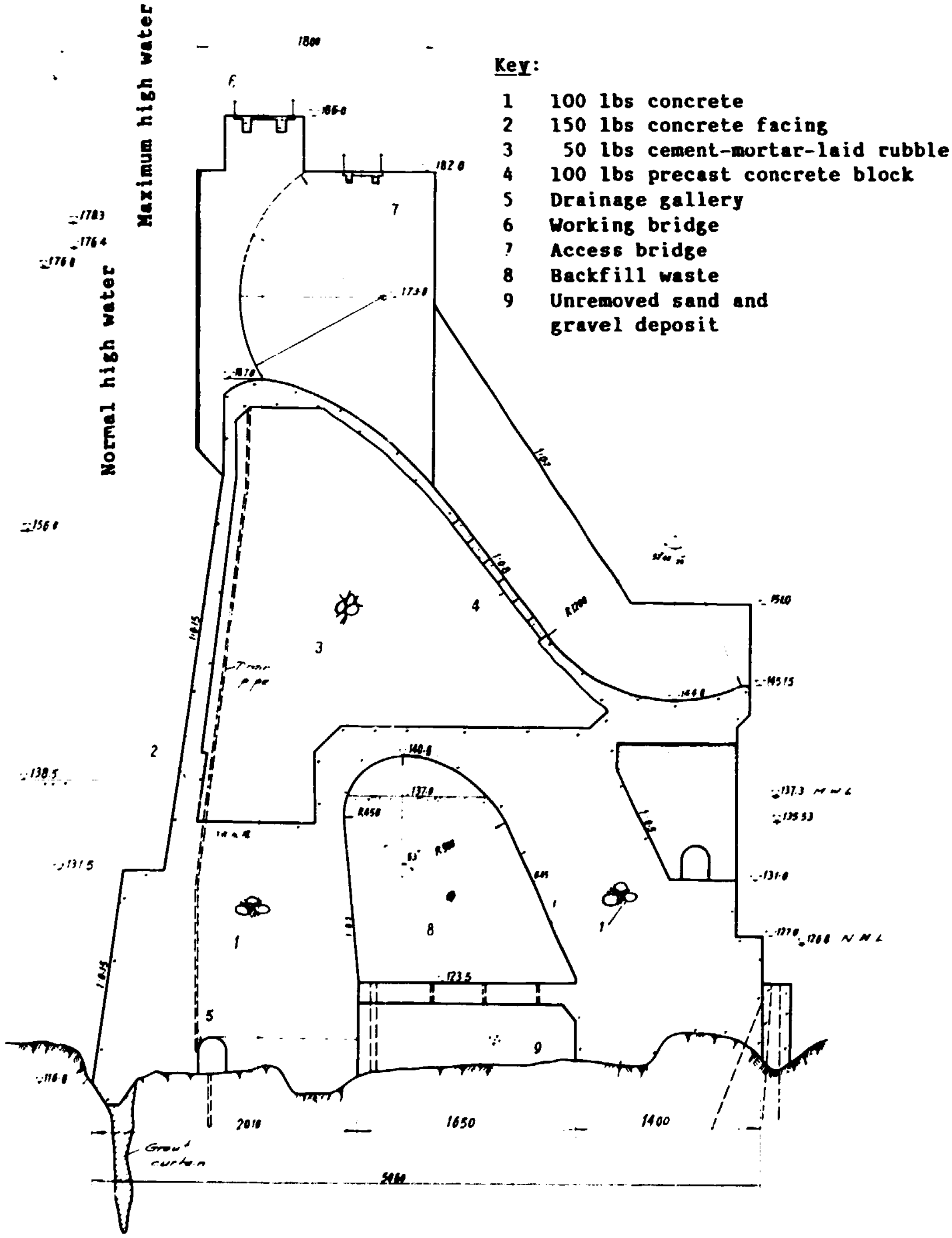


(b) Central core



(c) Inclined core

Figure 44. Yanwotan hollow gravity dam (cross-section)



Elevations: metres
Dimensions: centimetres

8-10 m. The length of the overflow masonry hollow gravity dam is 59 m and the maximum height 66 m. The width of the hollow cavity is 16.5 m at the bottom, the height of the cavity 24 m, and the cavity area 15 per cent of the dam cross-section. The foundation of the cavity part need not be stripped to speed up construction and reduce the uplift pressure. The construction period of the Yanwotan masonry hollow gravity dam was only 20 months, covering two dry seasons and one high-water season. The dam body was raised above the low-water level in only one dry season. During the high-water season, the dam body has been overflowed seven times for a total of 99 hours, but only five working days have been interrupted. The maximum overflow depth is 9 m.

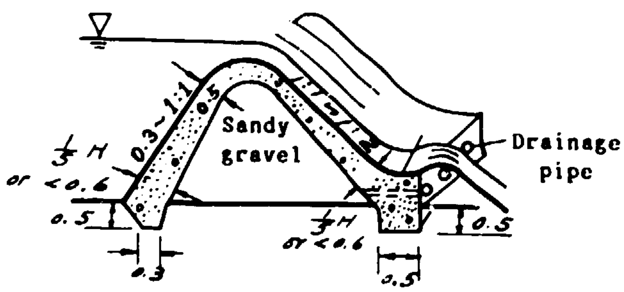
In a narrow valley with favourable geological conditions, a stone masonry arch dam can be built with thinner dam cross-sections and less volume, producing savings of 40-50 per cent in stone masonry and approximately 40 per cent in cement, as compared with gravity dams. In mountainous regions with wide river valleys, some stone masonry multiple arch dams have been built. In a stone masonry arch dam, the volume of stone masonry used could be from 30 to 50 per cent less than that of gravity dams.

Dams of simple construction

Hard-shell dams

Hard-shell dams are composed of dry-laid rubble or dumped sand and gravel as its main part and wrapped by rubble laid in cement mortar or by concrete as the hard shell in order to prevent seepage and erosion. The first example of this type of dam, built in 1965 in Guangdong Province, still proves satisfactory. In 1967, the same type of dam with a dry-laid rubble hard shell was experimentally constructed in Zhejiang Province (see figure 45). Hard-shell dams are suitable as low weirs on rock foundations in places with abundant sand and stone but insufficient soil.

Figure 45. Masonry hard-shell dam



Dimensions: metres
H = Height

Since the body of hard-shell dams consists of loose material and uncemented - that is, dry-laid - rubble, rock-fill or sand gravel, whenever any part of the hard shell is cracked it is easy for the entire dam body to collapse. Attention must be paid to both the structural design and the supervision of dam construction.

The foundation of the cut-off wall which also supports the hard shell must be properly treated, extending 0.5 m deep into the sound rock. It is not necessary to treat the foundation of the other parts of the dam. For example, a dam 17 m in height in Guangdong Province has an overburden 6 m deep. Only the sand and gravel at the cut-off wall have been removed. The overburden under the dam core is untreated. However, quality control of the dam core must be well supervised to avoid the unallowable settlement of the core which, as a result of separation between the core and shell, can cause damage to the dam.

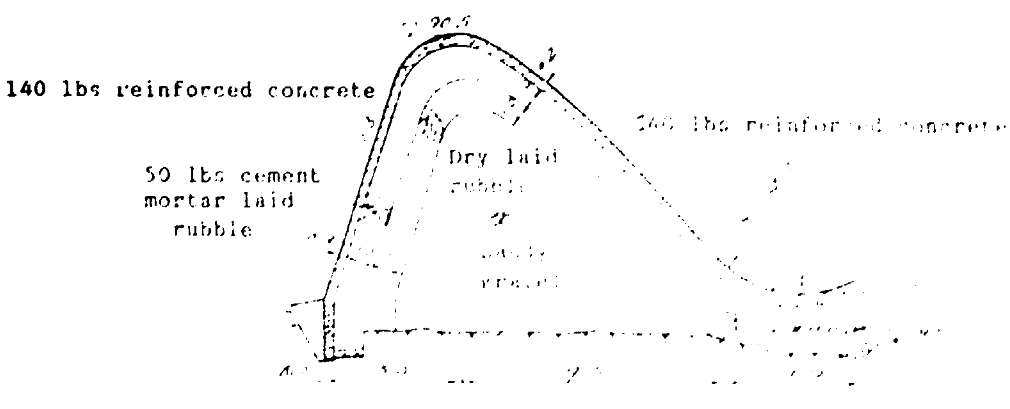
Structural design

In view of the convenience of construction and the reduction of the lateral pressure of the core, the slope of the upstream shell is selected as 1/0.3-1:1. The slope of the downstream shell is rather flat, usually taken as 1:1-1:2, in view of the overflow. It is preferable to form the arch action of the stone masonry hard shell, in which case, the shell will stand any settlement of the core. The slope of the shell may have an even flatter design if necessary.

The stability calculation of the hard-shell dam is basically the same as with the gravity dam. As the materials of the shell and core are different, different specific weights of material must be considered and different friction co-efficients in the foundation used. The core material is considered permeable. Uplift forces acting upon the core are neglected. The placement density of dry-laid rubble is γ_1 = 2.1 tonnes per m^3 (proportion of voids less than 25 per cent), of sand and gravel γ_1 = 1.7-1.8 tonnes per m^3, and of stone masonry shell γ_2 = 2.1-2.2 tonnes per m^3.

The hard shell is supported by the dam core. The thickness of the shell is 0.6-1.5 m in most cases, although 2-3 m is sometimes adopted for high dams. The outer shell is made of rubble laid in cement mortar plus the cement mortar facing, or rubble laid in cement mortar or concrete plus reinforced concrete facing (see figure 46). The thickness of the reinforced concrete facing is at least 0.2-0.3 m and will be increased for the curved parts. Both the longitudinal and transversal reinforcement steel bars are 6-9 mm in diameter. The spacing of contraction joints along the dam axis is not allowed to exceed 40 m.

Figure 46. Masonry hard-shell dam (cross section)



Dimensions: metres

At the downstream toe of the shell, there are drainage holes with [illegible] ted filters arranged beneath the bucket in order to reduce the seepage pressure on the shell. The holes are spaced 3 5 m apart with a diameter of 10 15 cm. The inverted filter has three grades to prevent ta[illegible] out the core material or blocking the holes.

In order to increase the rigidity of the hard shell, reduce the deformation and produce resistance to the possible lateral pressure of the filling materials, a stone masonry partition wall spaced at 10-15 m should be built along the da axis inside the hard shell. The thickness of the wall [illegible] 1-1.5 m (head _ 10 m). It has the advantage that in case of an emergency in some part of the dam, the safety of the dam as a whole will not be [illegible]

Construction techniques

After the foundation treatment is completed, the rubble laid in the cement mortar of the hard shell begins to lay up. There is a [illegible] crete cushion on the rock foundation of a major dam in order t[illegible] contact between the rock foundation and the masonry. The [illegible] be filled with cement mortar. In order to withstand lateral [illegible] the core material, the lift of the shell must be done [illegible] core material is inserted.

Experience has shown that the porosity of dry laid rubble [illegible] gravel [illegible] the core material is more than 30 per cent. [illegible] is only [illegible] tonnes per m^3. River sand is usually [illegible] voids by [illegible] and thus to increase the placement weight [illegible] cent. The sluicing of sand should be carried out layer by layer [illegible] are first laid in a layer 30 50 cm thick. Then, a layer of sand [illegible] is spread on top of it and sluiced to fill up the voids between [illegible] Essential reference data are given in table 25.

Table 25. Reference data for dams with a stone masonry outer shell

Discharge per metre (m^3/s)	Height of weir (m)	Width of top (m)	Cross-section: Upstream slope	
[illegible]	[illegible]	1.5-2.0	1:0.75-1:1	
[illegible]	[illegible]	2.0	1:1	[illegible]
[illegible]	[illegible]	2.0	1:0.75-1:1	[illegible]
[illegible]	[illegible]	[illegible] 2.5	1:1	
		[illegible]	[illegible]	

Dry-laid stone dams

The dry-laid stone dam does not need cement materials. It is mainly composed of rock-fill, gravel or sand and gravel, with dry stones on both the upstream and downstream slopes. This type of dam makes full use of local materials and may be constructed with a low investment.

In Guangdong, Zhejiang, Fukien, Sichuan and Henan Provinces, there are various types of dry-laid stone dams built using local materials and adapted to local conditions. Dams of this kind are more adaptable to larger deformation of foundation and can be built on sand and gravel foundations as well as on sand or earth foundations.

During construction, the demand for diversion of river water and drainage of foundation pits is relatively low. The laying of the stone can even proceed under water where the depth is less than 0.5 m. The excavation work is rather simple; only silty soil and sand and organic material will be removed. The shortcoming of this dam is its weakness in integration and seepage. To overcome these weak points, the selection of stone material and the dry laying must be strictly supervised.

A trapezoidal cross-section of this type of dam is given in figure 47, reference dimensions are presented in table 26, and figure 48 shows several types of dry-laid stone masonry dams.

Table 26. Reference data for dry-laid stone dams

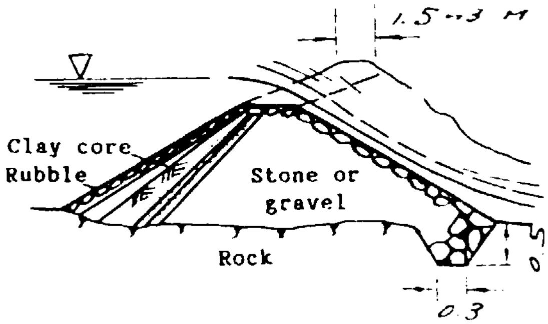
Type of foundation	Height of dam (m)	Discharge per metre (m^3/s)	Cross-section		
			Width of top (m)	Upstream slope	Downstream slope
Rock	<2	<3	1.5-2.0	1:0.5-1:0.75	1:1.5-1:2
Rock	<2	3-6	2.0	1:0.75-1:1	1:2-1:2.5
Rock	2-5	<3	2.0	1:0.75-1:1	1:2.5-1:3
Rock	2-5	3-6	2.0-2.5	1:0.75-1:1	1:3-1:3.5
Sand and gravel	<2	<3	2.0	1:0. [illegible]	1:3-1:3.5
	<2	3-6	2.0	1:0.75 1.1	1:3.5-1:4
	2-4	<3	2.0	1:0.75-1:1	1:4-1:4.5
	2-4	3-6	2.0-2.5	1:1	1:4.5-1:5

Table 27. Reference data for a Chaokuche-type dam
(Unit:metres)

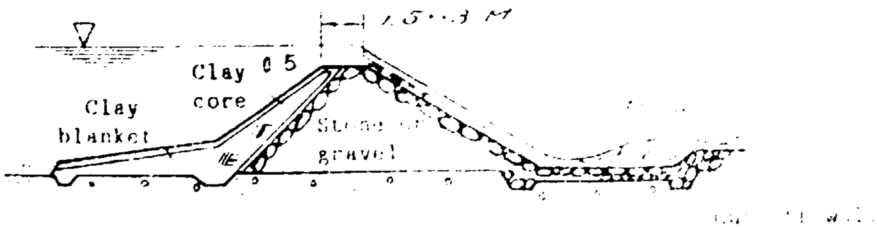
Height of dam	Over-flow depth (H)	Top width of dam (b)	Top width of dry-laid stones (B_1)	Bottom width of dry-laid stones (B_2)	Bottom width of rock-fill (B_2)	Total bottom width (b)	Thickness of each filter layer	Total thickness of filter layers	Height of upper-upstream slope (h_3)	Upper	Lower
10	1	2.5	1.5	3.5	10.5	14.0	0.2	0.6		1:1.5	1:1.5
15	1	2.5	1.5	4.5	15.5	20.0	0.3	0.9	5	1:1.5	1:1.75
20	1	3.0	2.0	6.0	20.5	26.5	0.4	1.2	10	1:1.75	1:2.0

<u>Note</u>: Reference symbols are keyed to figure 52.

Figure 47. Dry-laid rubble dam (cross-section)



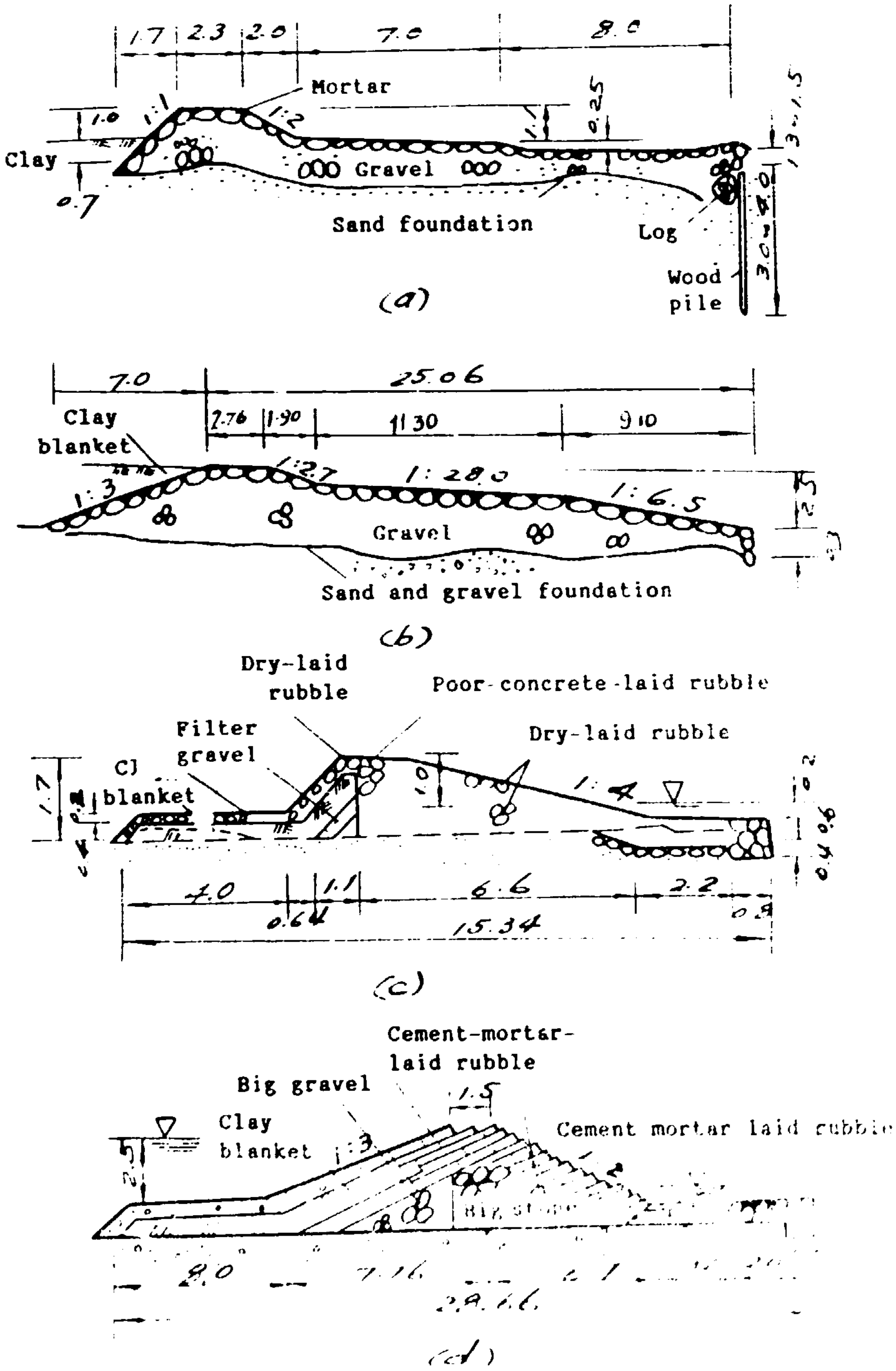
(a) Rock foundation



(b) Soil foundation

Dimensions: metres

Figure 48. Types of dry-laid rubble dam



Dimensions: metres

Seepage barrier for dry-laid stone dam

The main considerations in the design of a dry-laid stone dam are prevention of seepage from the dam embankment and foundation, stability of the dam slope and prevention of scouring of the downstream face.

In the dry-laid rubble dam illustrated in figure 47(a), an impervious sloping clay core is used with a slope of 1:1.5-1:2.0. The thickness of the core is 1/4 to 1/6 times the head and not less than 1 m at the bottom and 0.5 m at the top. At the upstream side, the core is protected by a layer of 15-20 cm of gravel and then a layer of 20-40 cm of dry-laid rubble rip-rap. Between the clay core and the dam body are two or three filter layers. If the river is rich in silt and the low dry-laid stone dams have no seepage barrier, the dam is permitted to seep during the first and second years. The voids will fill up with the silt from floods and a natural impervious sloping core and blanket will eventually be formed at the upstream face of the dam.

On a foundation with an overburden, a clay blanket is required in addition to the impervious sloping core, as shown in figure 47 (a). The length of the blanket is about 3-5 times the height of the dam and the thickness 1-1.5 m at the dam heel and 0.5 m at the upstream end of the blanket, where there is a cut-off.

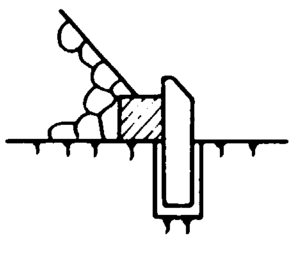
Apron

On unrocky foundations, an apron must be provided at the downstream toe. The length of the apron is taken as 2-5 times the height of the dam or 1.5 times the upstream water depth. The thickness will be more than 0.5 m. If the apron is made of dry-laid stone, the rubble must be tightly compacted and interlocked. Downstream of the apron, a protection must be made of dry-laid boulders or timber cribs with a rock-fill three to five times the length of the water head.

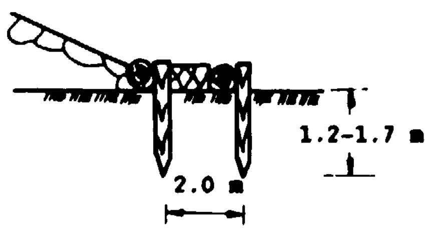
Foundation treatment

The key to foundation treatment for dry-laid stone dams is the treatment of the downstream part which is very important to the stability of the dam. In general, on a rock foundation, a 0.5 m cut-off trench is excavated and backfilled with concrete masonry, as shown in figure 47 (a). Another measure is to erect stone columns spaced every 3-4 m in the cut-off trench and a row of cut stone just upstream. On soil foundations, after foundation stripping, a group of timber piles with a spacing of 1 m should be driven 1.5-2.0 m into the ground and a row of logs put horizontally just upstream of the piles, as shown in figures 48 (a) and 49 (b). In addition, a downstream apron must be made to protect from scouring.

Figure 49. Treatment of the toe of a dry-laid rubble dam



(a) Rock foundation



(b) Earth foundation

Quality control

The use of small stones is prohibited, and large stone blocks 0.6-1.0 m in length, weighing over 150 kg per block, must be placed on the exterior slope, dam heel, toe, crest and other parts exposed to erosion. The rocks selected must be solid, durable and resistant to wearing and weathering. The stone blocks on the exterior slope must be very close together and the joints securely postioned at suitable intervals.

The construction schedule is usually to build the two abutments first and then build towards mid-stream. Upstream and downstream work can proceed simultaneously. The upstream parts may be slightly higher than the downstream parts. They must be connected at the top of the dam and compacted by solid stone blocks.

After the dam is put into operation, it is possible that settlement will occur, especially after the first flood. A large amount of seepage may also occur, causing some stone blocks to settle or loosen and even be washed away. Careful inspection and maintenance must therefore be carried out, particularly before and after each flood. Loose or washed-away stones must be quickly recompacted or replaced.

Dry-laid stone dams are widely used in small-scale hydraulic schemes. Figure 48 shows four types of this dam. In type (d), the cut stones are placed inclining upstream to prevent their being easily washed away and enable them to be arranged more compactly. The angle of inclination is 1:3-1:4. Figure 48 (c) shows a trapezoidal cross-section which is easier to build.

Overflow earth-rock dam

The overflow earth-rock dam is composed of earth and stone and easy to construct. Since 1956, many overflow earth-rock dams on rock foundations, known as the Chaokuche-type dam, have been built in Zhejiang Province. They are adaptable to such local conditions as narrow valleys, insufficient soil material, the need for large volumes of excavation for chute spillways etc. For example, the 20-m-high Laxia dam of the Chaokuche type was completed in 1966 (see figure 50). Its downstream facing is dry-laid stone masonry with an exterior slope of only 1:0.2. Upstream of the dry-laid stone is the rock-fill, on the face of which is laid a sloping clay core. Filter layers are placed between the sloping clay core and the rock-fill. The crest is protected by cut stone masonry laid in cement mortar so as to permit flood overflow (see figure 51). Since the river bed is made of hard granite, there is no facility for energy dissipation downstream of the dam. After several years of operation, with an overflow depth of less than 1.0 m, the performance is still normal.

The downstream facing of the Chaokuche-type dam consists of dry-laid stone blocks with an interior slope of 1:0.1-1:0.2. It contains a volume of 65-75 per cent dry-laid stone blocks and rock-fill and approximately 30 per cent earth. Since the dam body may be utilized as the flood pass during construction, no diversion is necessary.

The downstream dry-laid stone blocks sustain the lateral water and soil pressure from upstream, for which a solid rock foundation is advisable. The weight of each stone block must exceed 300 kg. Cut stone with a regular surface is preferable.

Figure 50. Laxia composite dam (cross-section)

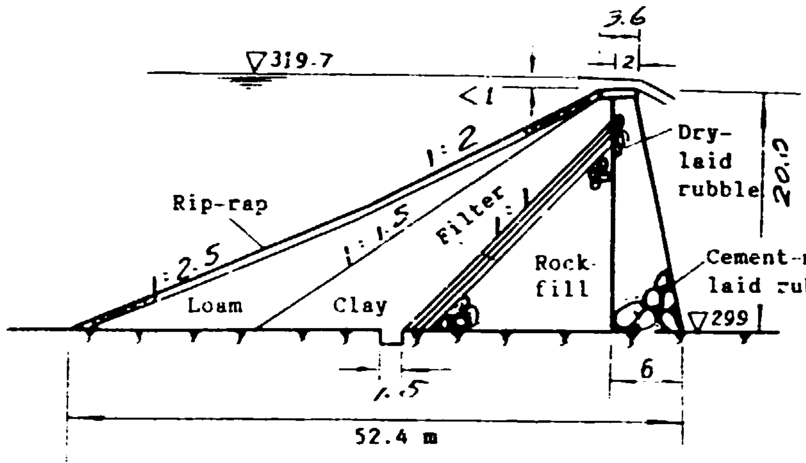
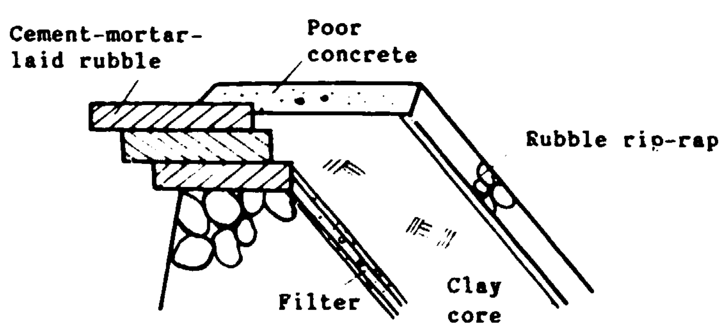


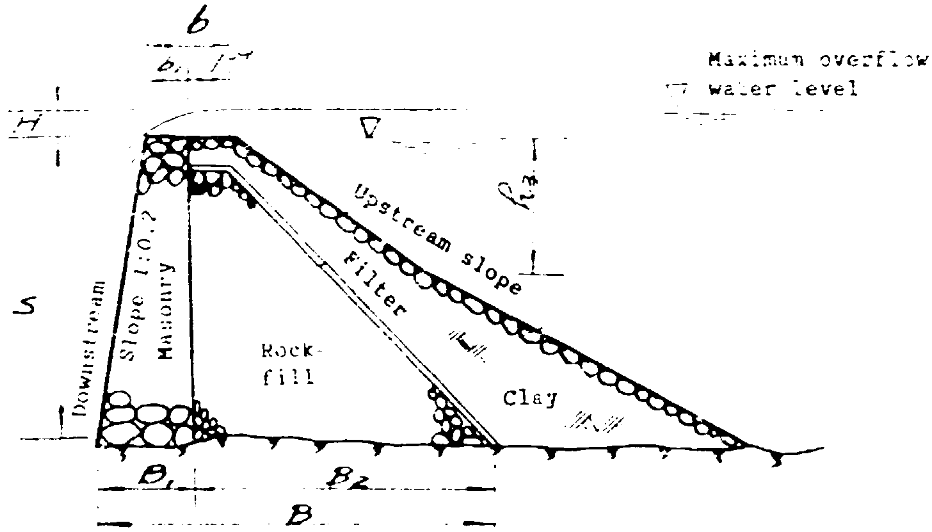
Figure 51. Structure of top of composite dam



The stone block joints should be staggered. The porosity of the rock-fill should be less than 30-40 per cent, with a placement density of 1.6-1.7 tonnes per m^3. Filter layers are placed between the sloping clay core and the rock-fill. The filter layers should be thicker than those of earth dams in order to fit more deformations. Quality control, particularly of the dry-laid stone blocks of the downstream facing, must be strictly and regularly carried out.

Reference dimensions of the cross-section of a Chaokuche-type dam are given in figure 52 and table 27. The maximum height and water head over the crest of a Chackuche dam are, respectively, 20 m and 1.0 m. When the height of the dam exceeds 15 m, a variable upstream face with two slopes is recommended.

Figure 52. Chackuche type dam (cross-section)



Rock-fill dam

Rock-fill dams are not generally designed as overflow types. Overflow rock-fill dams without facing are only used as weirs when they are below 3 m in height, as shown in figure 53. The upstream slope of the weir is 1:2-1:3 and the downstream slope 1:8-1:12. This implies a rather large volume. It is, however, still easily destroyed by flooding, and should therefore be built on sand and gravel river beds when rock material is abundant. Its building is rather simple and the cost low.

Longitudinal 1 m thick partition walls of rubble laid in 50 lbs. cement mortar are provided at 10-15 m intervals in the direction of the river flow. If the river deposit is shallow, the middle partition wall should extend into the rock. If the river is rather wide, transverse partition walls are also added. The spaces between the longitudinal and transverse partitions are filled with rock-fill, gravel and coarse sand and then compacted layer by layer. The weir surface stone masonry must be smooth and sound. The weight of the individual blocks should not be less than 50 kg. In order to prevent scouring downstream, a dry laid stone block apron, 2.5 times longer than the height of the weir and 0.5 m thick, may be provided.

Figure 53. Low overflow rock-fill dam