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NATIONAL IRRIGATION ADMINISTRATION
QUEZON CITY

MAGAT RIVER MULTIPURPOSE PROJECT

GEOLOGY REPORT
PART B

Consultants

E S E D

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF DRAWINGS

INTRODUCTION

General

This report is intended primarily to record the status of geology, up to the end of Part B, but it also mentions significant results of some subsequent investigations. As construction proceeds and more data are accumulated, details of interpretation will be modified and updated and covered in other subsequent reports or drawings if required. This report is in part adopted from the ESED Task Force Geology Report dated October 1977. The interpretations of regional and site geology as well as evaluations of foundation conditions for structures and potential associated problems are those of the Consultant.

Purpose and Scope of Investigation

The National Irrigation Administration recognized the potential value of regulating the Magat River to provide irrigation and power in Northern and Central Luzon and has embarked on studies for the Magat River Multipurpose Project. Present river regulation is confined to a low concrete gravity diversion dam at Sitio Ambatali, Barrio Oscariz in the municipality of Ramon. The diverted water is used solely for irrigation of a limited area of farmlands. The pre-feasibility and the subsequent feasibility studies conducted earlier by NIA indicate that the year-round irrigation potential of the Magat River can be increased to cover about 104,600 hectares, besides producing 540 megawatts of power which is much needed.

In early 1975, NIA embarked on a detailed review of feasibility studies made on the Magat River and subsequently entered into contract with an association of foreign and local consulting engineering firms known as ESED to act as NIA's consultants for the implementation of the proposed project. Field investigations were started in the early part of 1975.

In July of the same year, the detailed geological investigations of the project site commenced and have continued to the present. The various phases of the geological field investigations centered on establishing the engineering properties of the foundation for the proposed project, locating sources of construction materials and evaluating their suitability to the project scheme.

This report presents the regional geologic setting in general terms, the site geology in detail, as developed by the various investigation programs, and discusses the seismicity and engineering geology of the site.

Main Features of the Project

The main features of the Magat River Multipurpose Project include:

a. A rockfill embankment approximately 114 meters high and 3,960 meters long at the crest.

b. A concrete spillway on the left bank of the Magat River capable of passing flood flows on the order of 30,000 cubic meters per second.

c. Two parallel 12-meter diameter concrete lined tunnels on the right bank of the Magat River to divert the Magat River flow during construction.

d. A powerhouse on the left bank of the Magat River for the development of the 540 megawatt power potential of the project.

e. A small 15-meter high dam on Baligatan Creek to act as a diversion structure.

f. Modification of the present Maris Dam to increase its reregulation storage.

g. A transmission line from the power plant to the proposed NPC substation at Santiago, Isabela.

h. Rehabilitation of existing canals and drainage facilities of the Maris Irrigation Project and construction of a new system of canals to serve the new areas.

In addition, support facilities are also included in the project such as the development of camp facilities, erection of a bridge across the Magat River downstream of the proposed dam to be utilized during construction, construction of a small airfield capable of accommodating light aircraft and installation of seismic monitoring equipment with radio telemetering to a central observatory.

Methods of Investigation

The primary objective of the multi-phased investigation of the site was the gathering and assessment of data needed to develop the design for the proposed MRMP scheme.

Geological mapping of the proposed dam site was carried out at a base map scale of 1:500. The maps were subsequently reduced to 1:1,000 and 1:2,500 scale which were used for all presentation purposes. The base maps were developed by actual ground topographic survey using plane table, alidade, and stadia rods. In less critical areas further away from the dam site, mapping of creeks and other outcrops were carried out with the aid of compass and tape on base maps developed by photogrammetric methods from aerial photographs.

At the same time that surface geological mapping was being pursued, subsurface investigations were performed. As of the end of Part "B", diamond drilling cored more than

19,000 meters of the underlying overburden and rock formations; 363 meters of exploratory adits have been driven through the right bank of Magat River and more than 74,000 meters of dozer trenches have been excavated on both the left and right abutments of the dam.

Until March 1977, most of the subsurface investigations were carried out on the right bank of the Magat River as the proposed layout to that time utilized the right abutment as the foundation for the concrete appurtenant structures. However, after rejection of this layout by the NIA Board of Consultants (NBC) at its first site visit on March 23-26, 1977, the geological and foundation data on the left bank were brought to the same level of investigation as those of the right abutment by conducting more exploratory drilling and excavating systematically laid out dozer trenches. Thus, the data gathered were used in the development of alternative layouts for the proposed project which were presented to the NBC at the meeting in Vancouver, British Columbia, Canada on September 7-9, 1977. ESED's "preferred alternative" left bank scheme of development was approved by NBC from among the several layouts prepared and NIA directed that this scheme be adopted for the final design and construction, although ESED favored the right abutment scheme because of better foundation and topographic conditions. ESED, however, believed the left bank scheme was an acceptable alternate.

Surveys and investigations for construction materials included the search for impervious core, filters, rockfill and concrete aggregates. Auger drilling and test pitting in proposed borrow areas were made mostly by hand, with the aid of a backhoe traxcavator. A rock quarry was located above the left abutment of the dam and rock fragmentation in actual test blasts was observed. A test embankment was prepared from this material and then evaluated for its suitability in the proposed dam. MRMP set up its own materials testing laboratory to perform most of the required tests on the various construction materials. Other specialized tests were done at the University of the Philippines Industrial Research Center and other testing centers abroad.

GEOGRAPHY

Location and Access

The Luzon highway system connects the northeastern provinces of Nueva Vizcaya, Isabela, and Cagayan to the rest of the island by the Japan-Philippines Friendship Highway. All heavy equipment and supply items needed for construction have to pass along this road from the urban centers of Central Luzon.

The proposed Magat Project is located at Sitio Ambatali, Barrio Oscariz in the Municipality of Ramon, Isabela. Access roads to the dam site have been constructed by NIA-MRMP passing the old Maris diversion dam and connecting directly to the highway at the municipality of Santiago.

Pilot roads on both the left and right banks of the Magat River have been opened by MRMP for easy mobility of the equipment during exploration.

An airfield is being maintained by the Civil Aeronautics Administration at Cauayan, Isabela. Philippine Airlines operates flights to this town from Manila using jet propelled aircraft. The MRMP has completed a short unpaved runway for light aircraft near its campsite at Ambatali. During construction, this NIA-operated runway can be used by the Contractor as well as NIA-MRMP personnel, thus saving the one hour or so needed to travel to the Cauayan airport.

Topography and Drainage

The MRMP site lies close to the foothills of the eastern slopes of the Central Cordillera Mountains, the core of Northern Luzon. The geomorphology in the region suggests a middle to late maturity stage of development where landforms are becoming rounded with relatively gentle slopes and where the drainage channels are wide and approaching base level in their longitudinal profile.

The regional terrain reflects the underlying rock formations, that is the softer sedimentary rocks underlie valleys and wide depressions, while the more resistant lithologic units make up the ridges and promontories. In general, relief in the project area is relatively low. Maximum elevation is about 300 meters above sea level, whereas the river channel elevation in the vicinity of the damsite is 100 meters above sea level.

The Magat River is one of the major tributaries of the Cagayan River, one of the longest drainage systems in the Philippines. The Magat River channel has a U-shaped valley and wide floodplains, typical of a mature stage of development.

Regional Geologic History

Luzon consists of two crustal units separated by a major northwest-trending fault zone (Ligayan-Dingalan Lineament); each crustal unit consists of several blocks. The eastern block consists of the Sierra Madre Mountains, the Cagayan Basin and the Cordillera Central Range; the western block is composed of the Cordillera Central, the Central Basin and the Zambales Mountains. Major vertical movements occurred between these blocks. The basement complex of the Cordillera Central is found at an elevation of 6,000 meters below sea level in the Cagayan Basin.

The basement complexes of the Sierra Madre and Cordillera Central-Zambales were intruded by major dioritic stocks forming the roots for a series of sub-parallel volcanic arcs. The Sierra Madre is a geanticlinal unwarp with denuded volcanic arcs, formed during westward subduction of the sea floor generated in the Philippine Basin. East-west spreading in this basin occurred in the Eocene. Durkee and Pederson wrote that the Sierra Madre and Caraballo Mountains are composed of andesitic igneous rocks with early Tertiary bedded metavolcanics and metasediments along their margins. These mountains have formed a stable platform since the early Miocene. Uplifts of the Cordillera Central and Zambales blocks and accompanying volcanism was more or less contemporaneous with subsidence in the Cagayan and Central Valleys.

Drilling data indicate that in the early Miocene, deep trenches formed in which massive sequences of bathyal and abyssal sediments accumulated. In the late Miocene, these graywackes (turbidites) were covered by neritic shales and claystones, which in turn were covered by a regressive marine Pliocene sequence of corals and clastics and by fluviatile Pleistocene deposits. The Cordillera Central and Zambales geanticlinal upwarps, with their active volcanic arcs, originated from eastward subduction of the sea floor, most probably generated by spreading in the South China Basin. Available data suggest this eastward underthrusting may have commenced in the Oligocene after westward underthrusting below the Sierra Madre ended.

The oldest rocks on Luzon occur in the core of the Zambales and along the east flank of the Sierra Madre. The Zambales rocks consist of an ophiolitic complex (objected sea floor) of unknown age. Younger dikes intersecting folded units were emplaced in the Oligocene. Similarly, little is known about the metamorphic basement of the Sierra Madre, described as pre-Jurassic on the Geologic Map of the Philippines.

Much of the early Cenozoic history of Luzon was related to the emergence of the Sierra Madre volcanic belt. Therefore, it can be expected those volcanic formations now designated Cretaceous on the geologic map may prove to be younger after more detailed studies. Oligocene-Eocene basalts underlie the marine sediments of the Cagayan and Ilocos Basins with only slight unconformity.

The late Cenozic history was dominated by the emergence of the Cordillera Central and Zambales Blocks with their volcanic arcs. Deep basins flanking these geanticlinal upwarps were rapidly filled with sediment eroded from these highlands. In the late phases of uplift (middle Pleistocene), regional decollement stripped the sediments off the flanks of the Cordillera Central and caused broad folding of these deposits in the Cagayan and Ilocos Basins. Similar decollement occurred along the eastern flank of the Zambales.

REGIONAL GEOLOGY

Regional Stratigraphy and Structures

The MRMP site is near the eastern fringe of the Cordillera Mountain Range, which forms the western rim of the Cagayan Basin. The basin covers a fairly large area, bounded by the Sierra Madre Mountains to the east and the northeastern Luzon provinces of Nueva Vizcaya, Isabela and Cagayan.

Regional geological data which are presently available are largely scattered. The areas covered by the Sierra Madre Mountain Range, Cagayan Basin and the Central Cordillera are known to have distinctly varied geological structures and lithology. The Cordillera Mountain Range has a core made up dominantly of Miocene mafic to intermediate plutonic masses (mainly diorites), flanked by intercalated metavolcanics and metasedimentary rocks. The Sierra Madre Mountain Range, on the other hand, is dominated by a core of plutonic basement rock of probable Cretaceous to Paleogene age, rimmed by Oligocene to Upper Miocene sedimentary rocks and lava flows. The Cagayan Basin is covered almost wholly by a thick sequence of Middle Tertiary clastic rocks, with some interbedded limestone and splitic volcanic flows.

The regional structural grain of northeastern Luzon is dominantly oriented to the north-northeast, concordant with the valley trends of the Central Cordillera. The Cagayan

Basin has generally been regarded as a graben between the Cordillera Mountain Block and the regionally uplifted Sierra Madre Mountain Block. Mapping by the PNOC[1/], however, suggests a folded eastern rim for the Cagayan Basin.

Within the Cagayan Basin, the regional fractures are dominated by the essentially north-south trending Santiago and Cagayan Valley faults. Seismic events related to these faults are considered to have strong relevance to the MRMP project site. The Santiago Fault has been confirmed by PNOC seismic reflection data to be only 10 kilometers east of the proposed dam site. This normal fault is steeply dipping to the east with a measurable displacement of more than 2,000 meters and has been confirmed by PNOC to be at least 70 kilometers long. By following the physiographic lineaments of the longer Cagayan Valley fault at 40 kilometers from the site a strike length of up to 400 kilometers may be interpreted.

In the site area (see Drawing SK-GE-192) ESED geologists and the PNOC have identified three major directions of lineaments N70°E, N35°W and north-south.

The N70°E lineament trends roughly parallel to the Magat River at the site. Both the Korokan thrust fault zone in the left bank and the shear zone at Baligatan Creek approximately follow this direction. Recent drilling below the Magat River

1/ Philippine National Oil Company

has identified faulting which also trends about N70°E.

The main N35°W lineation, known near the site as the Nursery Fault, and which crosses the Magat River less than 3 km downstream of the site, has been identified from aerial photographs to extend for some 50 to 70 kilometers. Outcrops of this fault mark the thrust fault contact of two distinct rock types. The agglomerate-tuff series of the upper Zig-Zag Formation which occurs at the site overlies the sandstones and shales of the Lubuagan Formation which are found further downstream.

The third lineament direction is north-south and is manifested by a series of faults south of the dam site between Bagabag and Santiago and by the Magat Fault at the dam site. These lineaments were not identified north of the N70°E lineations close to the Magat River (see Drawing SK-GE-192).

The sedimentary rocks within the basin are generally tightly to broadly folded and their axial trends are following the same north-south regional trend. Locally along the right abutment at the dam axis (Drawing 1187-F-GEO-2146) a tight fold occurs with a N70°E axial trend that is plunging to the southwest. The northwest limb of this fold appears to have been overthrust by the agglomerate tuff sequence found on the left abutment.

Geomorphology

The physiographic features in the region reflect the lithology and physio-chemical characteristics of the underlying rocks. Where there are valleys and ridges, the bedrock is normally soft and hard, respectively. The wide valley of the Cagayan River has been cut through a thick sequence of interbedded clastic sedimentary rocks, while the bordering mountain ranges of the Sierra Madre and the Cordillera Central are generally underlain by more resistant igneous and regionally metamorphosed rocks.

Landforms reflect the regional geologic structures affecting the area. Lineaments due to faulting, jointing and continuous, truncated or tilted bedding planes are evident, especially where they mark the separation of two distinct lithologic units as at the Nursery Fault. Faults in the same type of rock, even though they are major, may be less visible geomorphically.

SEISMICITY

Regional

The most seismologically active zone in the Philippine Archipelago is that along the east coasts of the islands of Samar and Mindanao. The second most active zone extends from Luzon northward through the Bataan and Babuyan Islands and connects to the east seismic zone of Taiwan. There are shallow earthquakes in Western Luzon and off the west coast. Intermediate depth earthquakes usually occur inland. Several destructive earthquakes occurred along the Philippine rift, particularly in Luzon, Masbate and Mindanao; surface faulting has been associated with some of the earthquakes.

All of the epicenter plots (SK-GE-195) indicate that the northern Luzon region exhibits high seismicity, with those areas of significant epicentral concentration related to geologic and tectonic structure. There has been recent intense activity along the east coast of Luzon mostly the manifestation of the sequence related to the 1968 Casiguran earthquake and 1970 Baler earthquake and their aftershocks. An interesting feature of the seismicity plots is the concentration of activity in the Philippines east of the Philippine Fault. Except for the Mindoro Reentrant, the area west of the Philippine Fault shows moderate activity. Intense activity east of this fault may be due to renewed subduction along eastern Luzon with the Philippine Fault a secondary zone of accomodation.

Activity west of the Philippine Fault zone, particularly off the west coast of Luzon, suggests that subduction along the Manila Trench has not yet ceased. This trench, however, exhibits a low level of seismic activity. West Luzon Trough, on the other hand, shows moderate activity, particularly concentrated along its eastern extremity.

The location of large earthquakes provides guidance as to the capability of tectonic structures. Large, (Richter magnitude greater than 6) shallow earthquakes are common throughout the Philippines. Since 1900, the largest nearby earthquakes west of Luzon occurred in 1934 (M = 7.6 - 7.9) and 1948 (M = 7.2), in locations seaward of the Manila Trench, In central and southern Luzon, the largest earthquakes have been those of April 18, 1907, (M = 7.7), August 20, 1937 (M = 7.5) and April 8, 1942 (M = 7.7). Several large shocks occurred on the continental slope of Northern Luzon to the west. There is some concentration of epicenters in the Cagayan Valley area including that of the Isabela earthquake of December 29, 1949 (M = 7.4).

Historical data on all types of earthquakes shows that faults do not rupture over their entire length during any single episode of displacement but that the rupture length generally varies from one-fifth to two-fifth of the total fault length. The commonly accepted practice is to assume that 40% of the fault will rupture in one episode of underthrusting, however, before following this approach, it was necessary to examine earthquake data available in the Philippines and to investigate earthquake magnitude relationships peculiar to the Philippines.

On the basis of somewhat limited data, it was concluded that in the Philippines a smaller fraction of the fault zone may rupture in a given episode and these ruptures are associated with smaller magnitude earthquakes than observed elsewhere. Therefore, in view of the size and importance of the Magat Dam Project and the implications of a potential failure related to seismic activity, the faults governing the site were conservatively evaluated by using the commonly accepted 40 percent of fault length rupture in one episode.

Site

The site seismic considerations were based on a compilation, review and analyses of available historic seismic data for Northern Luzon and a study of the regional geology. Data from the following sources were considered:

- Manila Seismic Observatory.
- Weather Bureau (PAGASA), Manila.
- Gutenberg/Richter (1954).
- U. S. Coast and Geodetic Survey, Washington.
- Pasadena Observatory, Pasadena, California.
- Repetti, Seismological Bulletins of the Manila Observatory.

- o Seismological Laboratory, University of California, Berkeley, California.
- o National Geophysical and Solar-Terrestrial Data Center, Boulder, Colorado.

In addition, a recalculation of epicenters for the significant Northern Luzon earthquakes of December 29, 1949 and January 3, 1950 which had magnitudes of 7+, were carried out by personnel of the Seismological Laboratory, University of California, Berkeley. Early published data showed that these two events had the same epicenter location, approximately [illegible] km northeast from the dam site just east of the Santiago [illegible], while the recalculation indicated separate epicenters, approximately 48 km north and 105 km northwest from the dam-site respectively.

The international file of seismic events in Northern Luzon (January 1976), available from the Data Center at Boulder, Colorado, shows that in the past 79 years at least [illegible] seismic events larger than Richter Magnitude 5, which is the accepted approximate breakpoint for potential seismic damage to structures, have occurred within 320 kms. of Magat dam site. The actual number is probably much greater. Inadequate recording and loss of records between 1900 and 1950 are responsible for the existing shortage of data. Additionally, for technical reasons, the locations of some of the epicenters of the largest events prior to 1960 may be in serious doubt. Nevertheless, it is clear that many of the events having a Richter magnitude of 6, or greater, signifying a large earthquake, were either on or east of the Santiago Fault which flanks the west side of Cagayan Valley. This is especially significant since the long Cagayan Valley fault or faults are considered to be the origin of the highest magnitude earthquakes that will affect the Project site.

Study of the regional geology confirms the conclusions that the Santiago Fault marks a major break between the Cordillera Central Mountain system, where the Magat project is located, and the down-faulted Cagayan Valley system to the east.

Peak Ground Acceleration and Load Factors

For purposes of establishing seismic design parameters and the potential effects of a large seismic event on the dam and appurtenant structures certain assumptions had to be made.

It was considered prudent to establish design parameters on the basis of estimates of the effects of earthquakes occurring at four sources, as follows:

1. N-S trending, nearby, relatively small, potentially active fault (Santiago Fault);[1]

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(1) In this report faults are considered to be potentially active either if movement within recent geological time can be demonstrated or if the faults are regional and have a history of seismic epicenters associated with them.

2. N-S trending, major, but more distant, potentially active fault (Cagayan Fault);

3. Northwest trending, very close, relatively small, potentially active fault (Nursery Fault).

4. N70°E trending, potentially active faults at site (Korokan Fault Zone).

Figure SK-GE-195 shows a fault of moderate length passing within 10 kilometers of the damsite. This fault, having a north-northwesterly trend, has a length of at least 70 km. For conservatism, this fault was considered the "nearby relatively small, potentially active fault" and is assumed to be about 100 km long and 10 km from the site.

Structural and seismic data of Luzon Island indicate the probable existence of a long fault under the Cagayan Valley which can be extended offshore to the north. This north-south fault, which is 40 km from the site and may well be over 400 km long, is the "major, but more distant, potentially active fault."

Detailed site examination revealed the existence of a close potentially active thrust fault named the Nursery Fault. This fault is within 1 to 3 km from the site, is considered to be some 50 km long and trends northwest.

Site explorations revealed the presence of N70^{o}E trending potentially active faults, which regional studies by the PNOC have indicated to be some 25 km in length.

During Part B design, the structures were designed using the pseudostatic approach. Horizontal loads were obtained by applying factors of 0.3 (for concrete) and 0.2 (for fill) to the weight of the structures for use in the analyses. These factors were obtained in a normally accepted engineering manner as shown in the PDR and were based to a large extent on engineering judgement.

It was considered that the pseudostatic method of analysis was not adequate for the final design of a project the size of Magat. Hence a proper evaluation of the actual accelerations that can be expected to be generated by movements on faults has been carried out and is presented in the following paragraphs. More up to date design methods which take into account the responses of the structures to earthquakes will be adopted in conjunction with the more realistic assessment of loads applied by earthquakes.

START.

Characteristic	N70°E Small Fault	Nursery Small Fault	Santiago Small Fault	Cagayan Large Fault
Length	25 km	50 km	100 km	400 km
Distance from damsite	0 km	1 to 3 km	10 km	40 km
Richter Magnitude	4.7	5.7	7.0	8.0
Maximum Horizontal acceleration at epicenter	0.15g	0.52g	0.79g	0.84g
Duration above 0.05g at epicenter (seconds)	4s	15s	25s	40s
Maximum horizontal acceleration at site	0.15g	0.52g	0.48g	0.30g
Duration above 0.05g at site (seconds)	4s	15s	25s	30s
Principal frequency of major peaks at site	3-6 Hz	3-6 Hz	3-6 Hz	3-6 Hz

Although the N70°E faults occur at the site their maximum length, from the regional geological studies, is only on the order of 25 km and they have no history of known epicenters.

The Nursery Fault is located within 1 to 3 kilometers from the site and juxtaposes different rock types, however, the recorded seismic activity along the trace is limited to one cluster of low magnitude events. On the north-south projection of the longer, but more distant, Santiago Fault several large magnitude earthquakes have occurred. For design purposes it has been conservatively assumed that either the Nursery or Santiago Faults could be the source of the design earthquake.

Owing to the height of the concrete structures and their small period, the load factor would be expected to be somewhat higher than the peak ground acceleration. The actual amount of increase will depend upon the dynamic properties of the structures and should be analyzed using a response spectrum.

Because of the long period and considerable damping of the embankment materials the load factor for the embankment structures would be expected to be about 60% of the peak ground acceleration or less.

<u>Offsets</u>

Detailed aerial photo examination and field reconnaissance by ESED's consulting geologist, Dr. H. W. Burke, and the ESED site geologists have uncovered most of the potentially active faults at the site and traced their regional expressions. These data, coupled with the studies of Bonilla (1970), enabled a estimation of the magnitude of possible earthquakes and consequent surface displacements. It has been determined that the Nursery Fault, which occurs 1 to 3 km downstream of the site, has a surface trace of some 50 kilometers. The N70^{o}E trend, typified by the Korokan Thrust Fault Zone, has only been traced for about 25 km by the PNOC.

For the Nursery Fault, using the length of surface rupture and referring to Bonilla's charts, it is clear that a Richter magnitude 5.7 would be reasonable and would correspond to an average surface displacement of about 50 cm.

Seismic events with magnitude 7 are known on the Santiago Fault which is within 10 km of the proposed dam and average displacements along faults generating such a high magnitude earthquake could be on the order of 100 cm. Considering that higher magnitudes than the calculated M=5.7 and movement greater than 50 cm are possible along the Nursery Fault at a distance of less than 3 km from the dam structures, it is believed reasonable and not unduly conservative to consider a 50 cm offset along potentially active faults at the site.

The relationship between surface rupture, and earthquake magnitude also corroborate that movements on the thrusts at the site had to be incremental rather than occuring during one episode since the 10 m offsets measured at the site, i.e., at DF-63, would have required a magnitude 7.7 event with a length of surface rupture approaching 300 km.

It should be emphasized that a displacement of 50 cm along faults at the site is the maximum possible. It is considered that any significant movement during the life of the project is very unlikely. If any movement does occur it should be considerably less than 50 cm. Hence although the basic design of the structures takes into account a reasonable criteria, that is no movement on faults, prudent engineering dictates that the project features be designed to ensure no catastrophic failure should the maximum displacement occur.

Seismic Instrumentation

In view of the size and importance of the project and the seismic conditions outlined above, consideration must be given to seismic instrumentation at and in the vicinity of the site.

As a matter of broad principle, it is considered that the installation of a reliable and sophisticated system of seismic instruments (strong motion and sensitive seismographs) is a prudent step to obtain reliable information on seismic activities in the site area in the long-term. Such instruments should not however, be locally controlled and maintained, but should be, under long-term government supervision and operation by an agency dedicated to quality of maintaining and operating instrumentation and evaluation of seismic recordings.

In the absence of suitable recording instruments to measure the severity of earthquake ground motions and the response of the dam and appurtenant structures, the occurrence of a strong earthquake would pose many questions that could not be answered. If structural damage were to occur, there would be no way, without the measurements provided by the instruments, to compare behavior with design earthquake assumptions to estimate effects of other possibly larger shocks, or to make rational design decisions for any repair required to the structures at the site.

To date, both microseismic and strong motion instrumentation has been considered.

A tripartite network of sensitive microseismic instruments comprising one main station equipped with a 3-component seismograph and two substations, one equipped with vertical component, and one with horizontal component seismographs would be established in the area around the site and reservoir. Because of difficulties associated with transmission of signals from transducers to remote recorders, central recording systems are not recommended. A seismologist would regularly review interpret and disseminate the data obtained. Such surveys would provide base data for future use including the case that reservoir load induced shocks occur. Without such surveys, it would be impossible to establish the microseismicity of the area prior to reservoir filling. Thus, the extent to which local seismic events were a consequence of the reservoir or were part of a more general seismic pattern, could not be decided.

Strong motion accelerographs should be installed on the dam and structures. The recommended recording range is 0.01 g to 1.0 g. Again, because of difficulties associated with transmission of signals from transducers to remote recorders, central recording systems are not recommended. The desired locations for the strong motion accelerographs are as follows:

a. One instrument on each abutment.

b. Two instruments on crest (at different stations).

c. One instrument on downstream slope (0.4 to 0.5H above base of embankment).

d. One instrument on interface wall crest.

e. One instrument at crest near juncture of right spillway wall and penstock headworks.

f. One instrument in foundation (in drainage gallery under interface wall).

LOCAL GEOLOGIC SETTING

Site Geology

The MRMP project site is underlain by a thick sequence of rocks whose inherent fabric indicates a sub-aqueous depositional environment. These are correlated by PBGC geologists as an extension of the Upper Zig-Zag Formation, which outcrops along most of the southeast part of the Cordillera Central. The rocks consist primarily of agglomerate and altered tuff which are intercalated with thin beds of tuffaceous mudstones and siltstones. When unaltered and fresh, the rocks are generally competent and capable of supporting appreciable loads.

On the left bank of the Magat River, analcite basalt porphyry has been mapped, closely associated with the other rocks in an apparently conformable sequence. Dikes of lamprophyre dated to be of Lower Miocene age, occur associated with the Magat Fault and are occasionally found in the Baligatan Fault zone.

Approximately 3 km downstream of the site, the agglomerate-tuff sequence is in fault contact (Nursery Fault) with the relatively younger interbedded sandstone and shale underlying the western fringes of the Cagayan Basin.

A physiographic disparity between the left and right bank relief of the Magat River abutments is immediately noticeable with the left bank having a lower average elevation than the right. The left bank is characterized by a generally flat to gently sloping land surface as compared to the steep banks, moderately precipitous slopes and ridges and peaks found on the right bank. The topographic disparity is believed to be related to the more intense shearing on the left abutment which produced more easily erodible material. ✓

Lithology

There has been some controversy as to whether the lithology at the site represented sedimentary or igneous rocks. Field relationships clearly showed a mainly sedimentary nature as did the results of petrographic analysis performed by Dr. Robert Compton of Stanford University; however, some first generation pyroclastic materials are possibly also present. Although ESED recognizes this general sedimentary nature of the site rock units, it has agreed to the following nomenclature which incorporates terms used in the Philippines.

Terminology for Magat Site Geology

The following terminology for use in geologic mapping at Magat is consistent with the common practice in the Philippines of classifying any rock as agglomerate or tuff if it consists primarily of rock of volcanic or pyroclastic origin regardless of whether it is of first or second generation.

Agglomerate

The agglomerates are composed largely of water borne sorted and deposited material derived from a volcanic and pyroclastic regime and containing a considerable portion of fragments larger than sand size. First generation pyroclastic material may be included.

Sandy agglomerate contains relatively few fragments larger than sand size.

Granule agglomerate contains many fragments of granule size and few larger.

Pebble agglomerate contains many fragments of pebble size and few larger.

Cobble agglomerate contains many fragments of cobble size and few larger.

Tuff

Tuff is composed largely of water borne, sorted and deposited material derived from a pyroclastic and volcanic terrain and ranging in size from clay through sand. First generation pyroclastic material may be included.

Subdivision, where possible, are made on the basis of dominant size range, i.e., very fine, fine, medium, coarse or very coarse sand size.

Masses consisting dominantly of particle sizes in the silt and clay range are classified as mudstones.

Analcite Basalt Porphyry

Analcite basalt porphyry is the name given to a left bank unit which is recognized as analcite porphyry or analcite by ESED. Although most of the rocks in the area appear sedimentary, this unit is probably volcanic in origin and may represent a tuff-breccia. This unit has been mapped as intercalated with the agglomerate-tuff formation. This rock contains phenocrysts of well-developed crystals of analcite and some pyroxenes in a fine-grained groundmass. The analcite porphyry exhibits low grade alteration possibly due to metamorphism. Deeply chloritized analcite porphyry is common but its restriction to strong shear zones and faults probably indicates this type of alteration to be brought about by dynamic metamorphism accompanying stresses tending to ground deformation.

Lamprophyre

Minor dikes and sills(?) of lamprophyre were mapped intruding the agglomerate-tuff formation. They are localized mostly along the Magat Fault but also occur occasionally in the Baligatan Fault Zone. The lamprophyres are easily recognized in the field by their biotite content and the greater intensity of weathering compared to all other surrounding rocks. The lamprophyres are intrusives that are related to past volcanic activity in the region.

Clastic Sedimentary Rock

A few kilometers downstream of the dam site is a thick sequence of interbedded sandstone, siltstone, and shale considered by PNOC to be part of the extensive Lubuagan Formation found underlying a large area of the Cagayan Basin. This formation is in fault contact with the overlying agglomerate-tuff rocks along the Nursery Fault, where the Lubuagan Formation could be seen as steeply tilted beds with an imbricate fracture pattern. While the relative age has not been accurately established near the project site, PNOC has confirmed the northern part of this formation to be overlying the agglomerate-tuff formation.

Terrace Gravel

The term "terrace gravel" has been loosely applied at the site to include the semi-consolidated gravel and sand blanketing a sizeable area of the right bank of the Magat River as well as the fluvial gravel deposits occuring on the left bank.

The semi-consolidated deposits of the right bank consist of gravel to cobble size volcanic rocks, tuff and rarely other clastic rocks mixed and/or interlayered with dacitic sands. PNOC geologists claim that these deposits are similar to those which they have defined as the Tabuk Formation. Paleontological dating elsewhere in these deposits placed these detrital aggregates as Upper Pleistocene.

The fluviatile deposits on the left bank differ from the right bank gravels in that they do not contain dacitic sands. These alluvial deposits are considered to be younger than those occurring on the right bank of the Magat River.

River alluvium at the damsite consists mainly of sand and gravel deposits of volcanically derived rocks to depths of about 25 m.

The extremely to moderately weathered bedrock and the terrace gravels have been classified as part of the overburden in determining the firm bedrock at the dam site.

Geologic Structures

The Magat damsite is at the transition zone of two distinct tectonic provinces, giving rise to complex geologic structures. At the project site there are at least three major geologic structures, which may affect the stability of the proposed structural components of the project. These are the Nursery Fault, Magat Fault and Korokan Fault Zone, all of which are considered to be potentially active thrust faults. Other structures of engineering significance include low angle shears, imbricate joints and tightly folded rocks that are cut off by the thrust faults.

Nursery Fault

The Nursery Fault, so called because it was first recognized near the Baligatan Creek Forestry Nursery on the right bank of the Magat River, is a northwest trending thrust fault which crosses the Magat River some 3 kilometers downstream of the damsite. It marks the contact between the shales, sandstones and conglomerates of the younger Lubuagan Formation and the older agglomerate-tuff sequence which occurs at the site. The older agglomerate-tuff rocks overlie the Lubuagan Formation. The dip is steeply southwest to vertical. The fault is traceable for approximately 50 kilometers based on physiographic expression and lineaments which could be followed on aerial photographs.

The significance of the Nursery Fault to the stability of the site was stated by Dr. Clarence R. Allen in his report of June 24, 1977. In discussing surficial fault displacements at the Magat damsite, Dr. Allen said:

> "Virtually all large earthquakes and associated large fault movements have occurred on major through-going faults with long histories of recurrent displacement. Of all the faults in the site area, only the Nursery Fault can be demonstrated to have relative large displacement because it juxtaposes different rock types, although large displacements cannot be positively ruled out for the many breaks completely within the basement, such as the Magat Fault. Nevertheless, I would be grossly surprised at a major earthquake that was localized along one of the faults

within the actual foundation area. I would not be surprised, on the other hand, with minor sympathetic breaking along one or more of these fractures associated with a major event along a nearby major fault such as the Nursery Fault. All of these faults are thrust faults, and imbrication of the upper plate during thrust-fault earthquakes is more the rule than the exception. Assuming the major break to be east of the damsite (e.g., along the Nursery Fault), the site is in a very vulnerable position in this regard. I feel that the 50 cm displacement suggested by Dr. Burke for faults through the foundation is reasonable and not unduly conservative."

Magat Fault Zone

In the immediate vicinity of the dam site is the Magat Fault Zone which has a N20°W to N20°E trend and intersects the spillway discharge channel. As measured from its surface trace at the right bank as well as from underground workings (exploratory adits A and D), the zone of most intense shearing is about 40 meters wide and is composed of closely spaced parallel fractures with intense shearing and brecciation. In the most intensely sheared sections, as encountered at Adit A, mylonitic and gougy zones exceeding 10 meters in width are quite common. Within this 40 meter width of the fault, the intensely sheared rock is highly erodible. The fault zone also includes narrow sheared zones separated by relatively sound rock for an additional 100 or more meters downstream. The attitude of the shear planes ranges between N20°W and N30°E, dipping steeply towards the west.

Although extensive investigation by trenching was carried out, the fault could not be traced to the south further than the NIA Baligatan office, a distance of about 600 meters from the river.

Exploration on the left bank indicated a narrowing of the zone of intense shearing from a width of 40 meters on the right bank to approximately 15 meters at the left bank of the Magat River down to less than 10 meters, a distance of 400 meters further north where the fault is interpreted to be cut off by the strike of the DT-63 fault. Furthermore, the shearing on the left bank portion of the fault is not as intense as noted on the right bank. On the left bank, the Magat Fault is defined by two parallel fault zones a few meters in width separated by sound, sparsely jointed rock.

The DT-31 Fault on the right abutment was the first thrust fault to be recognized at the site where bedrock is overlying Recent gravel in fault contact. It has been suggested that this fault may be part of the Magat Fault but it could also be related to other northwest dipping thrust faults at the site since none of the characteristic lamprophyre of the Magat Fault has been identified at the fault or in DT-31.

Drill hole EB-21 intersected some material similar to the Magat Fault north of DT-63 but without the intense shearing characteristic of the fault. In trenches parallel to the river further north, the Magat Fault was not identified.

Exposures of the Magat Fault almost invariably show associated dikes and sills (?) of lamprophyre, which may be indicative of an appreciable depth of the fault. Parts of the Magat Fault have presumably remained dormant, at least after the emplacement of the dike, in view of the relatively undisturbed nature of some of the lamprophyre. However, other lamprophyre dikes have been sheared.

Korokan Fault Zone

The faults which are most significant to the project are those related to the N70^{o}E trending Korokan Fault Zone, since these faults are considered to be potentially active and underlie the left abutment of the proposed main dam and all left bank structures. The N70^{o}E direction is a regional trend, which is followed by the Magat River at the site, the valley under the embankment section north of the spillway and the Baligatan Fault Zone which was recognized for a distance of about 2 kilometers across the project.

The topographic disparity between the left and right banks is probably related to close, intense shearing of faults belonging mainly to the Korokan Fault Zone.

An analysis of the shears as seen in the left bank grout trench showed that there is a higher density of the subparallel thrusts between the river and the spillway location than to the north. Higher angle thrusts and features are more common than those of lower angle between the river and the spillway, while the reverse is true in the spillway area where the density of faults was also lower.

The Korokan Fault Zone was initially identified through the logging of bulldozer trenches on the left abutment in which a series of closely spaced thrust faults were identified. These faults were encountered in dozer trenches DT-15A, DT-44, DT-45, DT-46X, DT-62, DT-63, DT-66, DT-67, DT-68, and the left abutment grout trench. The significance of the faults in the dozer trenches was emphasized by fault offsets of the Recent gravels in some trenches, thus indicating the potential activity of the thrust faults.

The Korokan Fault, which was named after a small sitio on the left abutment, is considered to be the main fault of the zone largely because of its greater width and more intensely sheared material. This fault, however, is believed to be one of a series of genetically related independent strands that occur in the general N60°-70°E, 30°-55°NW attitude of the entire zone. Exceptions to the general attitude are some small thrusts on the left abutment which dip to the southeast. This anomaly might be explained by having an initial principal thrust direction from the southeast. This mechanism could have emanated from the active areas to the east and west of Luzon. It is believed that the thrusts originating from the northwest are the youngest thrusts since they override the tightly folded right bank sequence which contains thrusts dipping to the southeast.

As was mentioned earlier, the faults found in the trenches that offset Recent gravel, as well as parallel nearby faults without overlying gravel, are indicative of potentially active faults. Other faults were inferred in the left abutment although they were not identified by trenches or by offset of gravel. These faults were variously identified by topographic expression, depth to sound rock, attitude, springs, ground water levels or shears in borings. Identification of these faults did not require the use of all of the above items in each case, however, When these faults, without overlying gravel, were plotted and seen to follow the same trend as the potentially active faults whose classification was made largely on the basis of offset gravel, they were also considered as potentially active faults.

In his site visit of February 1978, Dr. Clarence Allen, in commenting on the Korokan and related faults, said:

> "Of the various faults observed, certainly
> the most significant are those related to

the Korokan Fault Zone,,because they pass through the left abutment of the proposed dam as well as appurtenant structures. But the Korokan Fault cannot be considered a single fracture. In both DT-15A and DT-45, at least two probable strands of the zone can be seen displacing gravels as distant as 50 m from one another; and the "DT-63" fault, although subparallel to the Korokan Fault, is not considered to be continuous with it. Still other strands of the zone would probably be seen displacing gravels in the left abutment area if the gravels were more widely distributed, as I emphasized in my report of June 24, 1977. Furthermore, because the Korokan Fault is clearly a thrust or reverse fault, imbrication of the upthrown block, northwest of the main fault, comes as no surprise, and the faults subparallel to the Korokan Fault in this block might well rupture in association with a movement on the main fault. Particularly in the absence of overlying gravels in parts of this area, one should be cautious in assuming that faults parallel to the Korokan (or Magat) Faults are necessarily inactive. Conservatism would, in fact, suggest the opposite assumption."

The present project layout places the appurtenant structures over some potentially active faults of the Korokan Fault Zone. This requires that the design of the dam and appurtenant structures be such that the structures could accept some foundation movement in the unlikely event during the life of the project of tectonic movements related to a large seismic event.

Although the DT-63 Fault is part of the Korokan Fault Zone, it is worth mentioning because of its 10 meter measured offset in the bulldozer trench where the bedrock is thrust over Recent gravels. In his February 1978 report, Dr. Clarence Allen described the faults in DT-63 and DT-46X as convincing proof that these features are indeed faults and not depositional features. Dr. Allen stated:

> "On the basis of this visit, I see no reason to alter the basic conclusions of my earlier report to ESED dated June 24, 1977. Indeed, the evidence for post-gravel fault displacements in the left abutment area is now more impelling than it was at that time, particularly in the light of the new fault exposures in DT-63 and DT-46X. These exposures are even more convincing of active faulting than was the original exposures of the Magat Fault in DT-31 (right abutment), which everyone seems to agree represents faulting of Quaternary gravels. In my opinion, there can be little remaining doubt of faulting of gravels in the left abutment area, including that of the dam foundation itself, and particularly along strands of the so-called Korokan Fault.
>
> The new exposures of faults in DT-63 and DT-46X are especially impressive because the trenches are deep and the good three-dimensional control leaves no doubt as to the geometries of the various faults. That these contacts truly represent faults and not depositional features is persuasively demonstrated by three lines of evidence, which are best shown where basement is in contact with gravels along the "DT-63" Fault in DT-63 and along the Korokan Fault in DT-46X.
>
> (1) The steep contacts between gravels and basement are in most places remarkably planar--much more so than would be expected if the gravels had been deposited against an exhumed and eroded fault surface.
>
> (2) All of the steep contacts dip between 40° and 61° "into" the basement rocks so that deposition would have to have been against overhanging cliffs with heights of

several meters. The highly weathered and fractured condition of the basement makes it exceedingly doubtful that such overhanging cliffs could have supported themselves without collapsing. Such relationships are, however, typical for thrust and reverse faults.

(3) Along most of these surfaces, marked gouge layers are present-- perhaps best displayed in DT-46X. Such persistent clay layers along steep contacts would be virtually impossible to explain by depositional processes. Furthermore, detailed textures in the gouge and adjacent rocks suggests shearing along the contacts."

Another prominent thrust fault thought to be related to the Korokan Fault Zone was found in DT-65 on the right bank and has an attitude of N40°E, 40°W. This fault diagonally crosses the open channel excavation for the intake portal of the diversion tunnel (Drawing 1187-F-GEO-2146 Sheet 1 of 2).

Recent drilling in the river has also indicated the presence of faulting, which may be related to the N70°E trend.

The Baligatan Fault Zone, which crosses the Baligatan Embankment Dam and runs parallel to and dips into the Baligatan Outlet Works trends N60°E and dips about 55° to the southeast (Drawing 1187-F-GEO-2146, Sheet 2 of 2). This thrust fault is believed to represent the older southeast dipping faults. An interesting point is that lamprophyre was found along some sections of this fault indicating a rather deep fault.

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Low Angle Shears

Numerous low angle shears have been encountered during the site explorations. The most notable of these are located between adits B and C on the right bank and in the left bank grout trench.

The low angle shears on the right abutment cliff between adits B and C are manifested as 20 cm wide sheared agglomerate and medium -grained tuff zones with some thin clay partings within the fractures. Most of the clay is presumed to be due to weathering. Slickensiding is traceable for about 25 meters along some fracture surfaces in the cliff. These low angle shears occur in parallel sets, are largely undulatory and apparently dip at 10 to 20 degrees away from the river. The lowest set occurs close to the normal river flow elevation. Along their strike projections, the low angle shears are cut by strong northeast trending bedding faults.

Low angle shears have also been noted on the right bank along the proposed dam axis near the old proposed spillway ogee section on the right bank spillway layout. These consist of NW-trending discontinuous shears dipping at low angles to the southwest or upstream. They occur in parallel sets cutting through relatively competent and moderately fractured agglomerate and tuff. Essentially, the low angle shears are asspcited with very narrow brecciated zones and contain some clay.

Low angle shears found in the left abutment bulldozer trenches and grout curtain trench are undulatory, generally trending north-south and contain sheared, brecciated rock with some clay. As in the right bank low angle shears, most of the clay is believed due to weathering. The left bank low angle shears appear to be more continuous than those on the right bank except for those exposed in the face of the right bank cliff. These shears, in some instances, seem to be contemporaneous with the Korokan Fault Zone thrusts since numerous examples of low angle shears cutting Korokan Zone thrust and vice versa are seen. In general, the left bank low angle shear zones may be slightly greater in width than those on the right bank. All appurtenant structures will be on low angle shears and their sliding stability is being carefully examined.

TMC

ENGINEERING GEOLOGY

Rock Properties

Laboratory rock testing has been performed on samples taken from the rock quarry, diversion tunnels and general project site to determine the design parameters for the foundation rock. Samples from the quarry area were generally tested for Unconfined Compression, Specific Gravity, Los Angeles Abrasion, Sodium Sulphate Soundness, Wetting and Drying, Schmidt Hammer, Void Index. Samples from the project site were tested for Schmidt Hammer, Void Index, Specific Gravity, Los Angeles Abrasion, Unconfined Compression. Samples from the Diversion Tunnels were tested for Uniaxial Compressive Strength, Young's Modulus, Poisson's Ratio, Density, Tensile Strength, Basic or Sliding Friction Angle on Rough Fracture Surface, Angle of Internal Friction and Cohesion. Results of testing from the rock quarry and the project site are presented in Volume V of the Main Civil Works Bid Documents. Some results of testing from the project are presented below.

The average strength parameters from the testing data are as follows:

a. Quarry (assumed to be all agglomerate). Average unconfined compressive strength = 418 kg/cm^2.

b. Project Site. Average unconfined compressive strength of agglomerate = 344 kg/cm^2. Average unconfined compressive strength of tuff = 241 kg/cm^2.

c. The summary of the intact rock physical properties for the diversion tunnel is:

Rock Type	C_0 (kg/cm^2)	E ($10^5 kg/cm^2$)	ν	γ (gm/cm^3)	T_0 (kg/cm^2)	ϕ_b (DEG)	ϕ' (DEG)	C' (kg/cm^2)
Agglomerate (Dry)	629	1.44	0.237	2.52	38	44°	62°	68
Agglomerate (Wet)	249	-	-	2.56	23	35°	55°	39
Agglomerate (Weathered)	293	0.52	0.24	2.32	26	26.5°	57°	41
Tuffaceous Mudstone (Dry)	855	1.8	0.22	2.52	61	35°	60°	119
Tuffaceous Mudstone (Wet)	-	1.7	0.24	2.57	34	39°	62°	61

Where:

C_0 = Uniaxial Compressive Strength

E = Young's Modulus

ν = Poisson's Ratio

γ = Density

T_0 = Tensile Strength

ϕ_b = Basic or Sliding Friction Angle on Rough Fracture Surface

ϕ' = Angle of Internal Friction

C' = Cohesion

The laboratory values of the unconfined compression tests for the quarry and for the project site in themselves should not be used by the designers without much caution. This is because values of unconfined compressive strength (and Young's Modulus) are from pieces of core without discontinuities and represent an upper limit for these strength parameters. The laboratory values must be reduced by a factor that would make the values consistent with the in-situ rock mass modulus which takes the discontinuities into account. Charts, such as those developed by Deere, give the reduction factors to be applied to laboratory results. These charts are directly related to the RQD (Rock Quality Designation) which are determined from the recovered core.

Without details of the individual rock tests, i.e., dimensions of samples, rates of loading, stress-strain relationships, only empirical correction values applied to the laboratory results can be used to obtain numbers for design. It must be noted, however, that these values could contain appreciable error since empirical values are just that.

In engineering problems where a measure of the direct reaction of a rock to a force is required, the values of the modulus of elasticity (E) and Poisson's Ratio (ν) are most commonly determined. The work of Judd and Huber, 1961, shows a linear relationship between rock compressive strength (C_0)

and the modulus of elasticity in the relation $E = 350\ C_0$. This relationship would then yield an average modulus of elasticity for the project site agglomerate of 1.22×10^5 kg/cm^2 and an average modulus of elasticity of 8.16×10^4 kg/cm^2 for the project site tuffs. These moduli are low indicating non-elastic rocks.

Since the true compressive strength of a rock is influenced by its internal structure, it can be concluded that a low compressive strength was due to a relatively large amount of pore space which is more characteristic of sedimentary rather than igneous rocks. The compressive strength of these rocks indicates relatively weak material, compared to values for other rocks, but of adequate strength to support the proposed structures. It is recommended that the uniaxial shear strength be taken as one half the compressive strength. It is assumed that the unconfined compression tests were performed on dry samples since the compressive strength of the rock is inversely proportional to the square of the percentage saturation to a minimum value of 45-50% of the dry compressive strength. This means that if saturated samples were tested, the rock can be considered to have a proportionately higher strength. If dry samples were tested, the designers should use caution in those areas where rock can become saturated. It appears that the site rocks lose strength because the saturated matrix or bonding material is rather quickly affected by weathering and/or saturation. For any design computations, the value of Poisson's ratio should be 0.25, adjusted according to RQD as discussed previously.

The rock testing that was performed on the diversion tunnel samples, although apparently more comprehensive than the field testing still must be used with caution as testing was done on intact samples without discontinuities. The same proportional reduction of test values to simulate the in-situ rock mass as described above applies to the diversion tunnel samples.

The average unit weights for the agglomerate range from 2.4 T/m^3 at the quarry to 2.5 T/m^3 from the project site samples. The average unit weights for the tuff range from 2.6 T/m^3 for the project site samples to 2.5 T/m^3 at the diversion tunnels.

MAIN DAM

The foundation for the main dam is mainly composed of interbedded agglomerates and tuffs with some mudstones. Although the foundation materials exhibit structural and textural differences on both sides of the river as well as in the river section, the foundation is judged to be competent to safely support the dam.

Most of the dam section will be situated on the right (south) side of the river as the majority of appurtenant structures are located on the left (north) side of the river.

The geologic conditions at the damsite are quite complex. The right abutment formations are composed of faulted, folded and sheared thinly to massively interbedded agglomerates, tuffs and mudstones. Exploration and construction trenches as well as road cuts and borings have confirmed a slight synclinal type fold with an axial trace to the northeast and a plunge to the southwest. This synclinal fold is often cut by numerous high and low angle faults. Some of these faults have been interpreted as being potentially active thrust faults but all right abutment faults are relatively minor as compared to those found in other areas of the project. The structure of the rock units at this location is interpreted as being the result of an early tectonic episode in which major units were complexly folded and faulted by a compressional force with a principal stress axis emanating from the southwest. The main evidence for this direction are prominent thrust faults trending about N70°E and dipping to the southeast. That this tectonic episode represented an older event is suggested by field evidence showing the synclinal fold apparently being cut off by the overthrusting of rock units from the left abutment. This later overthrusting had a principal stress axis coming from the northwest as evidenced by the numerous thrust faults that dip to the northwest and have their hanging walls facing to the southeast. The general north-south trend of the beds, seen downstream of the dam foundation in the vicinity of the Magat Fault on the right abutment side, are the trace of the beds of the northwest limb of the syncline swinging around to the southeast limb.

The foundation of the main dam in the river section is composed of interbedded tuffs and agglomerate. The rocks are generally striking to the northeast on the right abutment side and have been mapped as striking to both the northeast and northwest on the left abutment side with a point of convergence at about the dam axis. These differences in bedding attitude can probably be attributed to the overthrusting of the left bank formations onto the right bank formations. Recent explorations in the river indicate the presence of faulting, which may be related to the N70°E trend of the river at the damsite. The river alluvium is about 14 m deep at the river channel grout curtain and is not expected to exceed 25 meters at any point under the dam.

The left abutment dam foundation is also composed of interbedded agglomerates and tuffs which have been severely stressed by a system of rather closely spaced shears and faults trending essentially N50°-70°E and dipping to the northwest. The most prominent fault in this area is the Korokan Fault which is interpreted to be one of many parallel to subparallel shears and faults having the same general attitude and which are considered to be potentially active. Between the faults and shears of this zone the rock is often slightly weathered to fresh, but when taken as a rock mass the intense fracturing tends to reduce its strength parameters. The degree of shearing and faulting in the left abutment foundation can best be appreciated by referring to the Log of Grout Trench. This recently opened grout trench along the entire dam axis provided visual confirmation of the extent of this fault zone. Prior to the inspection of geological conditions in the grout trench, the Korokan Fault Zone was not well defined and some consideration was given to a possible shift in the locations of the appurtenant structures or the dam axis itself. The inspection of the geological conditions in the grout trench produced a picture that is believed representative of the general conditions on the left abutment and indicated that a shift of the concrete structures to other locations at the left abutment would not appreciably improve the foundation conditions for these structures. The trench was considerably deeper than previously excavated trenches and generally extended to the base of rippable rock. The geologic picture in the trench and environs was as follows:

> The area to the north of the Korokan Fault trace, extending to the northern end of the proposed structures, a distance of about 900 m, contains numerous shear zones, many of them shallow dipping, that may be genetically related to the compressional forces that produced the Korokan Fault and, therefore, could be considered as potentially active faults.
>
> The fractures and joints from the beginning of the rock in the trench, about 40 m south of the Korokan Fault, to beyond the northern interface structure are closely to moderately spaced, and show little variation in intensity.
>
> The material in the exposed shears generally consists of gravel to clay sized material from the Korokan Fault northward to about the base of the hill containing the spillway structure. In this hill the shear zones are composed of

ground rock of sand and gravel sized pieces. The average width of the shear zones is about 45 cm. Much of the clay infilling is believed to be the result of weathering rather than gouge material. At many locations the shear zones are relatively flat lying and undulatory, often grading into a steeper dip near the trench bottom. Some shears, however, become flatter at depth and are steeper at the surface. The depth of the trench enabled identification of the variable angles of the shears. It is believed that the flat lying shears are probably thrust faults whose low angle surface expressions were removed by erosion closer to the river. It is possible, based on the weathering of some of the shear planes and their relative topographic positions, that they may be contemporaneous or somewhat younger than the Korokan Fault.

The rock between the large shears is usually quite fractured but the fractures are tight and the rock is relatively sound.

The low topographic points along the grout trench axis are generally related to shears seen in the trench. The axis of the topographic depressions as well as the shears trend approximately N70°E. This is the same direction as the Baligatan Fault Zone, which is near the southern limit of the project.

The relatively wide low angle shear zones occurring across the grout trench steepen and extend to the surface; in all the shallower trenches which were previously excavated, very few low angle shears with width in excess of a few centimeters were encountered.

Based on the geologic conditions in the grout trench excavation and surrounding areas it was concluded that there was no advantage in adjusting the location of the concrete structures from those proposed in the present layout. Some adjustments, however, may be desirable after the excavation has been opened.

At the north end of the project is a smaller embankment which extends from the spillway structures to the left abutment. The foundation for this embankment is mainly agglomerate that is similar in character to the agglomerate under the Main Embankment Dam. The most prominent structural features of the foundation under this embankment section are the N70°E faults which are manifested by prominent valleys in the topography.

Foundation treatment for the main dam shells will largely consist of removing the extremely weathered to moderately weathered bedrock as well as any organic material and terrace gravels. For the core contact area the moderately to slightly weathered rock should also be excavated. Excavation of weathered rock will vary from a few meters to about 20 m; in the location of major shears the weathering may well extend to greater depths. An average excavation depth to an acceptable core foundation would be about 10 m. Dental work will be required where sheared and faulted zones are encountered in the foundation. Curtain grouting under the main dam and appurtenant structures has already been completed. Drainage galleries, to help dissipate foundation pore pressures, are currently being excavated.

END

DIVERSION TUNNELS

Two parallel 12-meter diameter concrete lined diversion tunnels are proposed for the right abutment. Tunnel No. 1 which is the south diversion tunnel has an intake to outlet excavated length of approximately 648 m and Tunnel No. 2, the north diversion tunnel, has a similarly measured length of about 565 m. A 615 m open approach channel connects the Magat River to the tunnel inlet portals. A short outlet channel returns the flow to the river.

The geology of the approach channel is composed of up to 15 m of terrace gravel underlain by interbedded agglomerates and tuffs. The beds strike about N40°E and dip to the southeast at angles varying from 40° to vertical. The rock in the approach channel ranges from extremely weathered below the overlying gravels to fresh at about elevation 125 to 130. The weathered zone, therefore, is about 5 to 10 meters thick. Rocks in this area generally have closely spaced fractures and many open rusty joints. Some brecciated zones were encountered. The major structural weakness in the channel is the DT-65 thrust fault which trends about N45°E and dips about 40° to the northwest. This thrust fault is interpreted as being related to the tectonism that produce the N70°E trend and would therefore be considered potentially active.

Cut slopes in the intake approach channel are expected to be stable if excavated 1V on 2H in overburden, 2V on 1H in rock on the south side of the channel, and 4V on 1H on the north side of the channel. The differences in cut slope on either side of the channel are a function of depth of weathering, the geometry of the planes of discontinuity and the prevailing weather directions. Berms are planned for elevation 116 and 126. Because of the depth of the tunnel approach channel, rebound of the rock with subsequent loosening of the rock mass will have to be expected at the portal face and side walls. It is suggested that rock anchors be installed as excavation proceeds.

Much of the tunnel is expected to be in fairly good rock but care must be exercised because of the slabby nature of the beds that will be intersected. The inlet portals for the tunnels will be excavated in tuffs. Rock at the structure is striking just east of north and dipping just south of east which corresponds to a direction sub-parallel to the tunnel portal axis in the intake area. It is just past the inlet portals that the rock reverses dip and a syncline is in evidence. As a consequence of this reversal in dip, the rock will dip steeply to moderately steeply towards the working face. This could, given the necessary conditions, result in potential wedge failure primarily from the roof. The conditions expected along the lengths of tunnels will be relatively constant throughout. That is, the rock will contain some small areas of highly fractured and open jointed planes along with some shear zones up to 4 m wide.

It is estimated that drilling operations in the tunnel face can pull 3 m rounds in good rock. Where good rock is encountered supports in the roof will still be required because of the ratio of the size of the tunnel to the joint spacings. Support systems for good rock are envisioned as rock bolts 6 m long on a 1.5 m by 1.5 m pattern in order to develop the roof arch.

Considering the relatively small cover and low RQD over the tunnels along their middle third, it is estimated that heavy shotcrete in conjunction with rock bolts or steel sets will be required, even if the rock appears to be fairly competent.

Where poor rock is encountered, supports at closer spacing will be necessary, and consideration should be given to pulling shorter rounds and to modification of the support system, for instance, full steel sets including invert struts. Regardless of the system used, it is most important to get the rock bolts, shotcrete or steel sets in place as soon as possible to prevent rock relaxation. The rock may have to be shotcreted to provide temporary support just before the steel sets are placed, and careful attention should be paid to proper lagging and bracing of the sets to allow transfer of load from the roof to the side walls. In the poor sections of rock such as faults or shear zones it is recommended that a spacing of steel sets of 1.5 m be considered, with field conditions governing the actual spacing. For these "heavy ground" conditions the lateral tunnel pressures are estimated to be 65 percent of the normal load in which case full supports, including the invert struts or foot beams anchored deep into the rock, will be required.

Cut slopes in the outlet channel will be IV on 0.75H down to sound rock at about El. 121 from which 4V on 1H cut slope will be used with berms at 15 m spacing.

In view of the potential for wedge-type failures and slope ravelling on the cut faces, due to rebound, adequate provisions should be made for the use of rock bolts and/or shotcrete.

BALIGATAN DIVERSION DAM

The Baligatan Diversion dam, located on Baligatan Creek, will be situated on members of the Lubuagan Formation. Geologic mapping at the site identified a basal conglomerate member upon which the diversion dam will be founded and a slightly younger shale with interbeds of siltstone and sandstones.

Borings and outcrops indicate a thin veneer of overburden of usually less than 3 meters. The rock underlying the overburden is generally fresh with some borings showing up to about 5 m of slightly to moderately weathered rock. The only exception to this depth is BDD-3 which has about 15 m of slightly to moderately weathered rock which can probably be attributed to the brecciation in the rock.

The area under the dam is composed of relatively massive pebble to cobble conglomerate which is probably the basal unit of the lower to middle Miocene Lubuagan Formation. The major structural unit in the area is the Nursery Fault located about 300 m upstream. Since the diversion dam is located on the footwall of the Nursery thrust, the bedrock conditions are unaffected by this major fault and the rock is relatively unfractured.

Where fracturing was noted it usually trends NNW-SSE with moderate to steep dips to the southwest. This attitude

BALIGATAN EMBANKMENT DAM AND DIKE

The Baligatan dike is the southern extension of the Magat Dam. It is situated on a series of interbedded tuffs and agglomerates that have undergone extreme tectonic disturbances. The main zones of weakness are the 40-meter wide Baligatan Fault Zone which trends about N45°E, 57°SE and another shear zone trending about N45°W, 70°SW.

The Baligatan Fault is interpreted as being one of the olde[r] thrust faults in the area, that is, it is related to the series that trends N50°-70°E and dips to the southeast. This fault zone contains shattered, pulverized, weathered, soft, erodible pebble agglomerate and includes an appreciable amount of gouge and clay. Test pitting in this area produced heavy seepage into the pit. Grouting is not expected to be effective due to the high clay content, much of which came from weathering processes after faulting. Much of the brecciated, crushed and fractured rock in this fault zone is in rock to rock contact and the zone is considered suitable as a foundation for an embankment with the main potential problems to be considered being seepage and associated erosion of the fault material.

The N45°W fault zone is an imbricate structure manifested by a wide zone of shearing and brecciation and including thick gouge within the fault zone. The fault material here is softer and more erodible than in the Baligatan Fault Zone.

In addition to the main structural defects noted above, many other orientations of faults and shears have been identified in this area. Geomorphic expression of parts of both North and South Baligatan Creek showing prominent north-south segments suggest that this is also a major structural direction.

The rock sequences between the major shear zones are certainly competent for construction of an embankment. In fact, the shear zones will also be competent with some treatment. It is recommended to excavate some of the poor shear zone material and replace it with material similar to that which will be used in the core. This will have the effect of strengthening part of the shear zone and reducing its erodibility. Relief wells should also be considered at the downstream toe to dissipate foundation pore pressures built up through seepage.

SPILLWAY

The spillway is situated on the left abutment in a complex of agglomerate mixed with some analcite porphyry and a lesser percentage of tuff. The geologic conditions in this area show the effects of intense tectonic activity which are manifested by numerous faults and shears of varying attitudes but which have a predominant set trending N50°-70°E and dipping moderately to the northwest. The general strike of the rocks in the headworks area also appears to be about N70°E as determined from the grout trench excavation. Surface expressions of bedding were not readily visible in this area. The grout trench near the spillway showed tectonically disturbed rock manifested by both the N70°E thrust faults and a system of low angle shears. The low angle shears have been found to be somewhat undulatory and, in many instances, cut off by the N70°E shears. This would indicate that the N70°E shears are generally younger but in some instances the low angle shears appear to cut off some of the higher dipping N70°E shears. In other areas the low angle shears appear to be somewhat discontinuous. They do, however, often contain slickensides and gouge which have a low shear strength. The grout trench indicated that there are intersections of low angle shears with steeper shears that may present stability problems for cut slopes and for resistance against sliding especially during earthquake conditions at a time of saturation of the fault or shear planes. A recommendation has been made to perform a detailed analysis of potential failure planes and their intersections along with determining the shear strength of the fault material. Laboratory test results should be available shortly and these data will be used for stability analyses to determine whether any additional excavation or remedial procedures such as rock bolting the slopes or providing a system of anchorage and/or foundation shaping against sliding in the foundation will be necessary. Excavation of the drainage galleries in the vicinity of the spillway headworks confirmed the existence of low angle shears at depth under the structures, but otherwise exhibited fresh fairly good rock conditions in contrast to the more weathered rocks seen in the grout trench. A drainage gallery will be installed in the foundation under the concrete structures at the left abutment. The primary purpose of the drainage galleries will be to dissipate pore pressures in a saturated foundation under controlled exit conditions.

Explorations along the chute portion of the spillway showed much the same type rock as at the headworks. Here, as well, are manu examples of shears in the foundation, and consideration of anchorage against sliding is necessary until stability analyses prove otherwise.

The flip bucket and the plunge pool area of the spillway are located in some of the poorest rock on the project. This is especially true in the plunge pool area near which the Korokan Fault and the Magat Fault intersect. The relationship between these two faults is not clear but suggests that the Korokan Fault displaces the somewhat older Magat Fault. Many borings and exploratory trenches have been made to define conditions in this area. The rock is essentially north-south trending agglomerate but with a greater percentage of tuff than towards the headworks. Some analcite porphyry is also present. Much of the flip bucket and plunge pool area has been affected by the intensity of thrust faulting related to the Korokan Thrust Fault Zone. Numerous shears are present along and across the bedding which have the overall effect of producing relatively small blocks of rock, usually less than one cubic meter. Rock blocks of this size, especially when close to shear and fault zones will be highly erodible under the dynamic forces of the spillway flows. Model tests are currently being performed which will give a better indication of potential erosion. From an analysis of the geologic conditions in the plunge pool and hydraulic model testing to date, it is estimated that erosion will go well below the plunge pool bottom of El. 80. An erosion level at about El. 50 is considered possible for the design flow conditions in portions of the plunge pool. The side slopes are also considered extremely prone to erosion. At this time, before the results of the hydraulic model tests are known, it is recommended that, as a minimum, consideration be given to protection of the flip bucket in the form of a curtain wall to prevent backward erosion that could undermine the flip bucket.

POWERHOUSE

The powerhouse is located on the left abutment just south of the spillway. The foundation material for the penstocks and powerhouse will be east-west trending agglomerate. This material is considered competent with the exception of those areas that are crossed by the potentially active thrusts of the Korokan Fault Zone. The main faults defined to date will be under the penstocks rather than the powerhouse. The section of the penstocks which crosses the potentially active faults should be designed for differential movements of the penstock supports.

Dental treatment will be required at any place the foundation for penstocks or powerhouse is underlain by a fault or shear zone. At present it is recommended to excavate the sheared material to a depth of about 3 m and to backfill with concrete. When the excavations are opened it will be possible to determine whether any of the moderately steeply dipping faults in this area are intersected by low angle shears which could cause a stability problem Remedial measures may then be necessary.

RIGHT INTERFACE WALL

The right interface wall, situated just south of the penstocks connects the left abutment appurtenant structures with the left side of the main dam. This structure, which is planned to be about 70 m high, will be seated in an area of agglomerate that contains a higher density of potentially active thrust faults than exists in other areas of the project. It is of special importance as it connects structures of different response to seismic acceleration. The location of this structure has already been shifted slightly northward to take advantage of somewhat higher ground, which has the effect of reducing the overall height. However, deep weathering in this area of highly disturbed rock may require excavation to lower elevations than anticipated, thereby, possibly resulting in a height of close to 80 m for this sensitive structure.

Dental treatment under the structure will be in the form of removing soft gouge and shear material from the foundation and backfilling with concrete. This will also apply to the low angle shears which are found under the structure and along its sides. These low angle shears often contain an appreciable amount of gouge. The depth and thickness of the low angle shears that have to be treated under the structure must be carefully analyzed.

RESERVOIR GEOLOGY

The reservoir geology is covered under a separate report by Engineering Geoscience, Inc. Numerous flights over the reservoir area have not revealed any appreciable areas of potential instability or of possible leakage.

CONCLUSION

The geologic setting at the proposed Magat Dam represents a suite of tectonically disturbed, pyroclastically derived, sub-aqueous deposited sediments. Detailed surface and sub-surface investigations supplemented by numerous laboratory analyses helped define the regional and site geology and the properties of the materials found at the site.

Numerous layouts for the dam and appurtenant structures were investigated and although none were without potential problems, it was determined that a number of project layouts, including the present one, could be engineered so as to provide an acceptable factor of safety for extreme seismic and other load conditions, that the dam and appurtenant structures can adequately be supported, after the necessary foundation treatment has been carried out.

Although the possibility that offsets could occur is considered to be very remote, during the life of the project, the design of the structures incorporates features which, for the maximum credible movements which might occur, would limit damage to non-catastrophic level by inhibiting and controlling the escape of reservoir water.

END