1930.
NEW ZEALAND.

ARAPUNI HYDRO-ELECTRIC POWER-STATION

(REPORT ON).

Presented to both Houses of the General Assembly by leave.

REPORT

RELATING TO THE DAMAGE THAT TOOK PLACE AT ARAPUNI HYDRO-ELECTRIC POWER-STATION ON THE 7TH JUNE, 1930.

In order to make it possible to propose suitable remedial measures for the damage that occurred at Arapuni on the 7th June, 1930, I have elaborated a definite theory as to the cause. The data that have served me in this work have been derived from inspections on the site in August and September, 1930, from discussions with geological and physical experts taking part in these investigations, from information given by the engineers connected with the works, and from various geological and technical reports previously submitted, and from certain drawings prepared by the Public Works Department.

The main factors that must be considered as having a possible influence on the occurrence, are as follows :—

(1) The geological character of the ground :
(2) The geomechanical properties of the ground :
(3) The periods of time during which the geomechanical agents have been working :
(4) Certain temporary phenomena, such as the subsequent closing of the crack, and the escape of nitrogen-gas out of the bottom of the head-race.

As regards the purely geological factors, I agree with the geological experts that there is no evidence of failure due to crushing in the columnar rhyolite tuff or in the underlying strata.

Concerning the geomechanical character of the ground, it has been ascertained by tests that the columnar rhyolite tuff and the underlying breccia possess some physical properties that deserve the greatest attention. These properties may be summarized as follows :—

(1) The columnar rock and the breccia absorb water avariciously when dry :
(2) They expand with absorption of water :
(3) They have an exceptionally small modulus of elasticity.

Considering the small modulus of elasticity of the columnar rock, the crack might tentatively have been attributed to hydrostatic pressure against the eastern side of the headrace, causing a compression of the ridge between the headrace channel and the river gorge, and/or a bending of the difference columns of the columnar rock like the bending of a laminated spring. I cannot accept this theory, however, as a complete explanation, because it is hardly conceivable that the country, under this assumption, could have remained intact during two and a half years' service after the water had been let into the headrace.

Again, the crack might have been attributed to the possibility that the pressure on the underlying strata at and near the power-house exceeded the crushing strength of these rocks, thus causing a rupture. If this were true, however, the movement should have continued when the very considerable hydrostatic pressure, due to water entering the crack, was added to the pressure that existed before the crack was formed. Furthermore, this explanation, which would have involved a permanent deformation of the rocks, does not conform with the fact that the disturbed block of the country, after the water had been lowered in the headrace, began to move back within a few hours and continued until the greater part of the distance towards its original position was covered. For the same reason it also seems unlikely that the crack is to be attributed to any settlement of the rocks due to a possible wash-out of fine material in the comparatively soft strata underlying the columnar rock.

It might finally be conjectured that the damage was due to the existence of open cracks in deeper strata, and that in these cracks water was impounded to a great pressure, consequent to an earth-movement closing the outlet from these cracks. I have not been able to prove beyond doubt that such causes of damage did not exist. Therefore this tentative explanation must not be overlooked with regard to remedial measures, even if it can be shown in the following that destructive forces due to other causes started to operate as soon as water was let into the headrace.

The primary cause of the rupture must, in my opinion, be traced back to the presence of water in the headrace. As the water cannot readily flow by gravity through the pores of the rock or in the narrow channels between different columns, the chief mechanical agent causing water to enter the rock must be attributed to capillarity.

The columnar rock at Arapuni, being of a porous nature, is particularly subject to the effect of capillary forces. This may be shown by the simple experiment of introducing a dry piece of the rock into water, when it is found that the liquid is avariciously absorbed. It is also easily conceivable that capillary action takes place in the joint planes between the different columns of the rock.

Capillary phenomena in natural ground assume many different aspects and constitute very complex problems. Every aspect of capillarity that may be conceived with regard to the case at Arapuni seems to contribute to a plausible explanation of the initial crack.

One of the most important characteristics of the columnar rock is the swelling of a dry piece of the rock when being saturated. Whether this is a direct or an indirect consequence of the capillary action is insignificant. It has been shown experimentally that the expansion per unit length due to saturation of a dry specimen is very great, amounting in one particular test to about 1 part in 2,000. Even allowing for the fact that probably most of the swelling takes place during the first stages of the saturation process, and the fact that tests have shown that the natural rock must have been nearly saturated before the water was let into the headrace, the residual swelling in the ground at Arapuni may account for considerable stresses between strata of unequal saturation.

Another aspect of the capillarity has reference to the presence of gas in the ground. There is every evidence that water has been brought by capillarity into the ground under the bottom of the headrace, thereby causing a compression of gases in the deeper strata. This aspect of capillarity may account for the eventual escape of remnants of air through the bottom of the headrace. It has not been possible to ascertain whether gases have also escaped from the deeper parts of the ridge. It is probable, however, that gases have also existed in these places, and that the gases have been compressed by the downward-travelling capillary water. The compressed gases have eventually tended to lift the overlying strata, and thus contributed to the cause of failure.

A further significant feature of capillary phenomena is provided by the time element. It is a well-known fact that cases occur when geomechanical processes due to a change of conditions where capillary action is involved take months, or even years, to develop before a new state of equilibrium is reached. This may explain why the rupture did not occur until two years and a half had elapsed after the water was let into the headrace. In this connection it should also be noted that the capillary water may have had considerable distances to travel. The columnar rock extends over a large area, including the down-stream part of the headrace, the tailrace below the spillway down to the falls, and the whole block of country bordering the river-gorge.

In view of the capillary characteristics of the columnar rock the rupture may be interpreted in the following manner :—

When the water was impounded in the headrace, a constant source for feeding into the capillary interstices of the columnar rock was created over a large area, and the level of this source was lifted 30 ft. to 40 ft. higher than the water-level of the swamp that had previously served as a supply of water to the rock.

It need hardly be explained that under the new conditions a certain amount of hydrostatic pressure developed in well-defined joint-planes of the columnar rock, where before there had been no such pressure, and where there had previously been a tendency to contraction, due to evaporation taking place from the ridge. In this way loosening of the joints would be effected.

The lower part of the columnar rock swelled to an extent corresponding to the difference between complete saturation and the saturation that had prevailed previous to the headrace being filled. The upper part and the overlying strata underwent very little change. Consequently, there was created a stress between the lower and the upper strata, tending to cause a break in the country.

Compression and bending stresses in the very flexible columnar rock behind the intake, and tensile stresses in the joint-planes in front of it, added a factor of instability to the ground. In this connection it should be noted that the tensile strength of the rock across the joint-planes is probably very small.

Any forcing-in of air into the deeper strata, which may have been brought about by the capillary action of water soaking into the ground, would also contribute a stress tending to cause a break in the country.

I believe that the splitting of the ground started at, or down-stream of the sharp corner between the intake and the spillway.

Once a crack had formed, certain internal stresses were automatically relieved. Water immediately filled the crack, developing the full hydrostatic pressure and widening the fissure until a new state of equilibrium was established between the hydrostatic pressure on one side and the elastic effect of the combined cantilever and beam action of the ridge on the other side.

Other subsidiary cracks appearing on the surface may be attributed to temporary phenomena due to the shock produced by the formation of the main crack. Whether or not some connection with deeper fissures was created at the occasion is uncertain.

Evidently the ridge between the headrace and the power-house has, during the accident, been subjected to a severe test load without failing as a dam. This indicates that the ridge will stand safely in the future, if it is adequately protected from the influence of destroying agents.

I am convinced that no rupture would have taken place if water under an increased pressure had been prevented from entering the ground in the bottom and sides of the headrace. I am equally convinced that no rupture will take place in the future if the cracks which have formed be effectively sealed and adequate measures, as proposed below, be taken to prevent the headrace-water from entering the ground.

The fact that the crack started to close up when the water was lowered in the headrace clearly demonstrates the great elasticity of the rock. It also gives the reassuring evidence that no internal failure due to crushing of the rock or washout has taken place in the ridge or in the underlying strata.

The fact that the crack has not completely closed is to a great extent due to the obstruction produced by material washed into it from the headrace. What remains of the crack indicates that there is still some compression in the columnar rock of the ridge, which will remain as an initial stress in the future, tending to restore the ridge to its original position.

Obviously, the ground under the power-house, and the structure itself, have also been subjected to very great stresses due to the movement of the ridge. The fact that the building nearly regained its old position shows that the foundation is uncrushed and well capable of taking its normal load. Also, it may be said that the various concrete structural elements have very well withstood the severe condition temporarily imposed upon them through the rock-movement.

Remedial Measures.

If it were assumed that, at any time, any part of the ridge could break away from the adjoining country, leaving open cracks of some magnitude, it would be hardly possible to suggest any preventive measures, at a reasonable cost, which would remove the possibility of a recurrence of trouble similar to that which occurred on the 7th June, 1930. The remedial measures to be taken must, therefore, be focused on the necessity of preventing any such cracks from forming in the future.

It may safely be assumed that the block of country in which the crack has occurred was in stable equilibrium before the river was diverted into the headrace, so that any remedial measures should be directed to maintaining the hydrological conditions in the state in which they originally existed.

The question arises as to whether the presence of the existing crack has increased or lessened the possibility of future earth-movement. At the present time there is about the same amount of water draining into the headrace as would correspond with the hydrological conditions existing before the plant was built. The conditions of equilibrium of the block of country are, however, not the same. The crack has separated the country into two parts, removing whatever support existed between them prior to its development. Even if the crack is filled with concrete the conditions will still not be the same. Due to the elastic properties of the rock, tending to bring the ridge back to its original position, the ridge will be exerting a greater pressure against the country to the west than was formerly the case. This residual stress in the ridge will tend, of itself, to prevent the formation of similar cracks in the future. It might thus be said that the damage that occurred at Arapuni on the 7th June provided the means of giving the ground an additional stability to that existing when the works were first begun.

I have come to the conclusion that the hydrostatic pressure of the water on the bottom and sides of the headrace will not, in itself, cause a dangerous earth-movement, provided such remedial measures as are proposed below are carried out.

As regards the future, it is the forces brought into play due to the soakage of water into the ground that need the most careful consideration.

To those who share my conviction that the impounding of water in the headrace brought about an increased penetration of water into the rock, and that the effect of this, together with the elastic properties of the rock, has been the primary cause of the damage, it may seem logical to attempt to safeguard the stability of the ground in future by means of preventing as far as possible the absorption of water. There is, however, reason to believe that such measures, if carried out too extensively, might lead to serious trouble. This will be easily understood if one calls to mind the effect of changes of moisture on the appearance of clay surface. When a clay ground surface which was originally saturated with water becomes thoroughly dry, very extensive cracks are produced; in some cases fissures as much as 2 in. wide are produced within a few feet of one another. As is well known, this effect depends on the capillary and colloidal properties of a water-clay mixture. The water evaporates from deeper and deeper layers of the soil, and at the same time capillary forces cause water to be raised from the lower strata, causing thereby a contraction of the soil, of which the cracks give ample evidence. It is not suggested that the columnar rhyolite tuff has all the properties of a clay from the physical point of view, but the analogy may serve to make clearer the meaning I wish to convey.

Phenomena of a similar nature would, undoubtedly, occur if the ridge between the headrace and the river-gorge were, for instance, covered with an impermeable layer which would prevent rain from replenishing any loss of water from the pores and joint-planes in the columnar rock below. I feel convinced that the provision of an impermeable covering over the ridge between the headrace and the river-gorge, which would allow the underlying rock to dry out, with a consequent contraction and production of deep, though possibly small cracks, would create a new danger rather than act as a safeguard.

Another suggestion that has been given consideration is that of digging open ditches in the surface to increase the run-off of rain-water, but I am very firmly convinced that the stability of the country is best safeguarded if, after closing the present cracks with concrete, the whole ridge between the main dam and the falls is left in its present state. There is no indication that the natural stability of the ridge between the headrace and the gorge has been impaired; rather do my deductions lead me to believe that the strength has been improved. It would seem, therefore, that the leaving of the processes of evaporation and replenishment by rainfall along the ridge to counterbalance one another, as they have done during geological ages, is the best method of maintaining the stability of this part of the country.

A similar consideration applies to the ground under the headrace itself. After a careful study of all conceivable factors relating to this question, I have arrived at the conclusion that it is of no great importance whether rain-water is or is not prevented from having access to the ground under the actual headrace. If anything, an advantage would be gained if rain-water was able to find its way on to this part of the ground, as in this way there will be no change produced in the present state of saturation of the ground.

I have assumed in the foregoing that all the cracks are to be filled with concrete. This assumption refers to such cracks only as reach the surface of the columnar rock. There may, however, be cracks that are located at greater depths and that do not reach this surface. It may be difficult to grout these cracks, and may even be dangerous to attempt to do so, as an imperfect grouting might obstruct the drainage of water from such parts as are left open, and thus make possible the accumulation of water under high pressure. Instead of an attempt to grout deeper located cracks, I propose that in the lower strata of the ridge drainage-tunnels be arranged at right angle to the axis of the ridge.

It is, of course, essential that the large volume of water that is impounded above the spillway to a depth of some 30 ft. should not be given any opportunity of soaking into the ground or causing any alteration in the capillary condition due to the considerable hydrostatic pressure from the headrace. This can be prevented in different ways. A system of pipes or a flume carrying the water to the intake and to the spillway can be arranged, or the bottom and the sides of the headrace can be provided with an impermeable lining, separating the water in the headrace from the ground.

There is no difference between these arrangements as far as the penetration of water into the ground is concerned. They differ, however, in relation to the pressure against the sides and the bottom of the headrace. Not only the pipes, but even the flume, can be arranged so as to relieve the sides of the headrace from hydraulic pressure; should only a lining be arranged, the hydrostatic pressure against the headrace would remain the same as before. It is, therefore, necessary to show that this pressure does not constitute a dangerous element, before the lining can be compared with the other arrangements mentioned.

In my investigation as to the cause of the rupture that occurred on the 7th June, 1930, reasons were given showing that the primary cause of the rupture cannot be traced to the hydrostatic pressure against the side of the headrace. I have also in the present part of my report drawn attention to the circumstance that the crack which still exists offers a means of making the ground more stable than it has previously been. This refers especially to the efficiency of the ridge between the headrace and the river, considered as a buttress against water-pressure from the headrace. I must, consequently, draw the conclusion that the hydrostatic pressure on the side of the headrace cannot cause a new earth-movement if it is not assisted by other agents of destruction.

There remains, however, a conceivable source of apprehension which I find it convenient to deal with in this connection.

Several small cracks have been detected in different structural parts of the intake. Either they must be effectively grouted or the intake must be rebuilt. I do not hesitate to recommend that the first of these two measures be taken.

Even so, we may not be quite sure but that there may be also small cracks in the rock behind the intake, and if these should not be effectively filled with a resisting material they would obviously constitute a source of danger, if hydrostatic pressure were exerted from the headrace.

Although less obviously, such cracks would if left open, be dangerous, even if an independent flume or a system of pipes were substituted for the present open headrace. The smaller the cracks are—if there are any—the smaller the quantity of water that would fill them; and water percolating during a long period of rain might cause serious damage. It must therefore, at all events, be considered necessary to employ methods of grouting by which there is a fair prospect of reaching all cracks not only in the structural parts of the intake, but even in the rock under and behind the intake.

Concerning the boreholes that must be made for the injection of cement mortar, the best method is, as is well known, to arrange the boreholes at an angle to the plane of the cracks, and, the cracks being in this case presumably vertical, the boreholes must be at an angle to the vertical plane.

These circumstances make it seem possible to arrange at a comparatively small cost such reinforcement of the ground as would make it able to resist any conceivable stress that may be occasioned by the hydrostatic pressure against the side of the headrace. If the boreholes are arranged in a suitable manner, the extra measure to be taken will be limited to introducing into the boreholes steel rods, which, embedded in cement mortar, are capable of dispersing the pressure over an area large enough to resist the hydrostatic pressure from the headrace. A reinforcement of this kind, is, in my mind, very advisable all along the intake. It should under no conditions be omitted in places adjacent to the junction between the intake and the spillway.

In connection with the grouting of the intake, all small-sized bodies between cracks in the concrete should be replaced by fresh concrete. I recommend, furthermore, that in front of the corner between the spillway and the intake a solid concrete block should be arranged from the first screen to the first dividing pier in the spillway, thus covering the first opening in the spillway. As to the details, I recommend that this block be not solidly jointed, but isolated from the spillway and the intake. The joints at the face should be cut out and filled with wedge-shaped strips of a plastic material to act as a seal and so effectively give a tight joint even if a small movement, due to compression or variations of temperature, should tend to open the joint between the spillway and the intake.

As to the intake, I finally recommend that, after all the open spaces under, in, and behind the intake have been thoroughly grouted, all concrete surfaces facing the water in the headrace be thoroughly cleaned and provided with a very carefully applied gunite concrete lining.

After this indication concerning the solidification of the intake and the rock behind it, I will now proceed to a closer comparison between the different measures that may be taken in order to prevent the possibility of water in the headrace increasing the penetration of water into the ground.

From this point of view there is no material difference between a flume and a system of pipes, but a flume would be by far the cheaper. I therefore discard the pipes in favour of the flume.

When comparing the flume with the lining of the headrace, certain constructional features may be considered.

I foresee that, in the case of the erection of a flume, difficulties would be encountered as to the jointing of the flume to the spillway, and to the intake, because the flume must of necessity be a more or less rigid structure, and yet must call for flexible joints in places to allow for expansion and contraction.

I also feel inclined to disapprove of the flume because special measures would have to be taken in order to make allowance for every conceivable change of the ground, no matter where or how small it be. For this reason, and also having regard to changes due to variations of temperature, the more the flume is calculated to transfer stresses from the intake to the spillway, and *vice versa,* the less it corresponds to my conception of an adequate solution.

No matter what measures are taken in order to safeguard the stability of the ground, the country as a whole will retain properties relating to plasticity, and, in my mind a plastic lining of the bottom and the sides of the headrace is more in conformity with actual conditions.

I am convinced that such a lining can be arranged so as to prevent effectively water from entering the ground, even if, contrary to my expectations, cracks should tend to occur in the ground.

As furthermore, comparative estimates have shown that a lining can be arranged for less cost than a flume, I confine myself to indicate in the following how I think the lining should be arranged.

First of all, the debris and all weathered material on the rock should be taken away.

Then porous layers of crushed sound rock, gravel, and coarse sand should be spread out, starting with the coarsest and finishing with the finest layer. The individual pieces of rock may have edges 1 in. to 3 in. long; the sand need not be finer than $\frac{1}{16}$ in.; the gravel may vary between these limits.

The materials should be arranged as in a filter, graded so that the layers of different-sized materials do not mix. The total thickness should be from 8 in. to 12 in.

On top of the sand a plastic layer should be arranged, consisting of bituminous material, and some metallic sheet, such as Robertson's protected metal sheet, arranged in plates overlapping each other. This layer should be protected by concrete slabs, the joints between which should be sealed by hot bituminous material.

The lining should be extended all over the bottom and the sides of the headrace to a height of 2 ft. above the highest computed water-level. The porous layers should reach the same level, but in the upper part of the slopes they should consist of gravel and coarse sand only—this in order to avoid a violent inrush of rain-water.

Where at the sides of the headrace the surface of the rock cannot be laid bare without removal of great masses of soil, retaining-walls may be considered. They should be watertight, and have a watertight connection with the impermeable lining in the bottom of the headrace, and they should be backfilled with earth to the level of the top of the wall.

Along the intake and the spillway structures the impermeable lining in the bottom should be arranged so that its edge will end on a rising grade overlapping the concrete, and so as to allow of minor movements.

A draining-trench filled with crushed sound rock should be arranged under the bottom, in the longitudinal axis of the headrace. At the lower end of the headrace connection should be arranged between this trench and the investigation tunnel that opens out into the air north of the power-station. This tunnel should be concreted to a certain height above its bottom.

Observation-pipes, reaching down to the porous layer under the headrace, should be arranged at the sides of the headrace. The top of these pipes should ordinarily be closed.

From the point of view of absolute security there is no doubt but that it would be advisable to extend the lining to the foot of the cliff that serves as abutment for the main dam; but I cannot advise it, because I believe that there are fair prospects of gaining at less cost a satisfactory result.

I propose that the lining be extended up-stream to a line about 350 ft. up-stream of the last outcrop of columnar rock at present visible in the bottom of the headrace.

At this extremity the lining should end in a trench at right angle to the headrace, and up-stream of the lining the trench should be filled up with concrete, making the surface in transition places as smooth as possible.

At a certain distance down-stream of this trench a gallery is arranged in the bottom and the sides, and in the country adjacent to the sides of the headrace. As the object of this gallery is to remove, partly at least by evaporation, the water that by capillary action or otherwise percolates from the headrace up-stream of the lining, the gallery should open into the air by means of one or more shafts arranged in the country adjacent to the sides of the headrace, and a tunnel connecting the bottom of the gallery with the river-gorge.

As to the action of these remedial measures, a few words may be added.

The aim of the porous layer under the impermeable lining of the headrace is twofold: it serves as a means of preserving the natural moisture of the ground, and at the same time to give warning should a rupture in this lining occur. As, in my mind, a rupture is possible only in case of an earthquake or a tectonic movement due to other causes, the first sign of it should immediately call for emptying the lake through the diversion-tunnel. I would, therefore, in order to prevent any future disaster, propose that a device be installed signalling instantly any exceptional increase of water in the drainage-tunnel north of the power-house.

The more importance I give to the aforesaid porous layer, the more strongly I recommend that it be arranged with proper care and with the use of proper materials. There is a theoretical possibility that it might partly clog on account of weathering of the underlying rhyolite rock. I feel, nevertheless, convinced that it will serve its aims if carried out properly.

I finally draw attention to one circumstance—the lining will greatly add to the stability of the spillway.

For reasons partly akin to the reasons calling for a lining above the spillway, I recommend that a watertight concrete lining be provided immediately on top of the rock below the spillway extension.

REPLY TO THE ORDER OF REFERENCE GIVEN BY THE MINISTER OF PUBLIC WORKS.

(1)-(1*c*).

(1) Are the general surroundings, the class of country, and the power-development possibilities such that the locality was suitable for the economic generation of hydraulic power?

> The general surroundings, and the power-development possibilities at Arapuni are such that the locality is very suitable for the economic development of hydro-electric power. Concerning the class of country, it may be said that it by no means excludes the possibility of creating a successful water-power station on this site.

Also under this heading replies to the following:—

(*a*) Whether it is likely that the country supporting the lake is capable of continuing to retain the weight of water, having special reference to the part known as Acacia Gully; if it is not capable of continuing to retain the weight of water, what steps, if any, are recommended to create adequate strength; and an estimate of the cost of carrying out such strengthening work?

> I have no doubt but that the country supporting the lake is capable of continuing to retain the weight of water. According to information obtained, the special reference to Acacia Gully has been raised mainly because the water-level in the Acacia Gully has shown a certain correspondence with the water-level in the lake. However, this correspondence does not necessarily imply that there has been an underground stream of water running from the lake to the Acacia Gully. When the water-level in the lake is raised, the ground-water in the plain between the lake and the Acacia Gully is also raised, and thus an increased quantity of water from the plain itself is drained towards the Acacia Gully. No water, however, can run from the lake into the Acacia Gully as long as the ground-water level in the plain is higher than the water-level in the lake.
>
> Thus the only way to ascertain whether there is a ground-water stream running from the lake to the Acacia Gully is to find out, by means of borings, the ground-water level in the plain. Such borings should be made, and the ground-water level in them should be subjected to investigations, especially during dry seasons. In view of the comparatively small average gradient between the water-levels in the lake and in the Acacia Gully, and considering the nature of the ground, I feel inclined to believe, however, that there is no likelihood of a ground-water current creating a breach in the Acacia Gully.

(*b*) Whether the main dam is correct in its location, design, and construction, having regard to the nature of the country, the weight of water the dam is required to support under full head, the ultimate proposed power output, and the public safety?

The main dam is correct in its position in regard to the ultimate proposed power output.

In regard to the public safety, it may be generally said that the stability of the dam proper under full head complies with the main rules now universally conceded as governing the design and construction of a solid gravity dam.

There is evidence, however, that the dam is leaking at some places in the foundation, even at the present lowered water-level with the river at its original stage. In all probability the leakage will increase when the water-level in the lake is raised. It is essential that the origin of any appreciable leakage be located, and that the leaks be carefully grouted under pressure, so as to stop effectively the water passing under the dam or through the rock foundation.

Any leakage which takes place after the lake has been raised should be recorded, and analysis should be made to ascertain whether the escaping water dissolves minerals or carries away particles of fine material during its passage through the country. I have been informed that analyses for this purpose have been made with satisfactory results, but the observations and tests should be repeated when the dam is again filled.

(*c*) If, in any particular under (*b*) the answer is in the negative, how and at what cost do you consider such shortcoming(s) may be rectified?

The country between the headrace and the river-gorge next to the western abutment of the dam is comparatively narrow—indeed, narrower than the block at the power-station which moved on the 7th June, 1930. The appearance of the rock, and the fact that no disturbance of the ground has been noticed in the narrow ridge at the abutment, indicate that the rock at this point is of a more reliable quality than that at the penstock intake. In spite of this evidence, however, it is my firm opinion that this part of the plant should be strengthened, and that the opportunity should be taken now to execute this work.

Also, the cliff at the eastern abutment up-stream of the dam to a point well above the entrance of the diversion tunnel should be strengthened.

This work should principally consist of a thorough grouting of the country, a gunite cover on the surface, and a reinforcement of heavy steel bars set in drilled holes in the rock as described in my report in connection with the remedial measures for the penstock intake.

(2) Assuming the reply to No. (1) to be in the affirmative, do you consider that the best use was made of the topography existing?

I consider that the best possible use has been made of the topography existing on the site.

(3) Were the works sited in such a way as to ensure the development of the maximum power available consistent with reasonable expenditure, and have the works as executed been designed in accordance with the accepted principles of engineering?

The works are sited in such a way as to ensure maximum power available consistent with reasonable expenditure.

In my report and under certain clauses of this order of reference, I have put forward the need of some strengthening and repair works.

There may be other points in the design inviting discussion, but, as these are more or less a matter of opinion between different schools of engineering, they are of minor importance in this connection. In general, it may be said that the works as executed have been designed in accordance with sound principles of engineering.

(4) Are there any points in connection with the scheme on which you have reason for adverse criticism ? If so, give particulars.

All my reasons for criticism have been laid down in my report and in my reply to the other clauses of the order of reference.

Also reply to the following question :—

(*a*) Whether, in view of the geological formation between the gorge and the headrace and spillway, the locations of the spillway-weir, the penstock-tunnels, the outdoor station, and the power-house are situated in the best relation to each other from the viewpoints of (*a*) electrical engineering practice and (*b*) civil engineering practice ?

From the civil-engineering point of view I have no adverse criticism to pass upon the general location of the different parts of the plant in relation to each other.

On the electrical side of the problem I can make no comment.

(5) Has the constructional work been well carried out ?

As far as can be seen from a detail visual inspection on the site, the constructional work has been well carried out.

(6)–(7).

(6) Was the cracking which took place on the 7th June a phenomenon which should have been foreseen by those responsible for the installation ?

(7) If your reply to No. (6) is in the affirmative, what steps do you consider should have been taken to prevent this cracking ?

When it is taken into consideration that the nature of the ground at Arapuni is so complex and unusual that, even now after the occurrence of the rupture and with new information available as a result of special investigations subsequently carried out, opinions differ widely as to the exact cause of the rupture, it may well be said that no reproach can reasonably be supported by such principles of engineering as were generally accepted prior to the occurrence. It must not be forgotten that most hydraulic engineering undertakings of great magnitude contain items of uncertainty ; that the number of such items increases in proportion to the number of unusual geological factors involved ; and, last but not least, that the designer is morally bound to try to reach his objective at the smallest possible cost consistent with a reasonable prospect of safety. I want also to express the opinion that, at Arapuni, no rupture would have occurred had the bottom and sides of the headrace been provided with a suitable watertight lining. The original plans and specifications indicate that the Public Works Department was not unmindful of the possible necessity of lining portions of the headrace, and I do not think, in the light of information known prior to the failure, that the engineers responsible took an unjustifiable risk in not lining the headrace originally.

(8)–(8*v*).

(8) What, in your opinion, was the cause of the cracking ? Also reply to the following points :—

(*a*) To what extent, if any, the following factors contributed towards the fracture in the hill between the gorge and the headrace and spillway :—

(i) Geological weaknesses in the headrace ;
(ii) The driving and operation of penstock-tunnels ;
(iii) The weight of the outdoor transformer station ;
(iv) The moment exerted by the weight of water in the headrace and spillway as a force applied against the hill in the direction of the gorge ;
(v) Weakening of the hill by water absorption.

The cause of the cracking which took place on the 7th June has been thoroughly discussed in my report, to which I refer.

In reply to section (iii), I am of opinion that the weight of the outdoor transformer station had no appreciable influence on the fracture in the hill.

(9) Does the fact that the crack occurred render the continued operation of the power-generating station impossible, presuming remedial measures to be carried out ?

The fact that the crack occurred does not render the continued operation of the power-generating station impossible, provided remedial measures, as proposed, be carried out. For further views regarding this question I refer to my report.

(10) Could the present power-house be safely operated without any major remedial measures being taken, and could the displacement of the generators be remedied ? Would it be possible or advisable to run the plant in the present condition of the machines and concrete emplacements ? If not, what should be done to remedy this position ?

I believe that the present power-house can be safely operated without any major measures being taken.

The question whether it would be possible or advisable to run the plant in the present condition of the machines must be solved in collaboration with the manufacturers of the machines. In this connection I would call special attention to the necessity of investigating if, in view of the cracks in the concrete around the scroll-cases, the twisting moment due to a possible short circuit in the generators is safely carried down to the foundation.

(11) Having in mind the condition of the fracture which exists, do you consider it advisable to construct any additional penstock-tunnels on lines of present existing tunnels ; and, if so, what would be the effect of the increased strain or pressure which would thus be placed on the hill between the headrace and the gorge ?

I do not consider it inadvisable, or involving risks due to increased strain and pressure, to construct the additional penstock-tunnels on the line contemplated. However, as the blasting in the tunnels and at the site of the power-station extension might have some loosening effect on the joint-planes of the columnar rock, I would suggest that the work be executed with great caution.

(12)–(14).

(12) Is the scheme put forward by the Department's engineers for remedial measures the best in your opinion, and could it be carried out at the price estimated ?

(13) If your answer to No. (12) is in the negative, which other of the possible schemes put forward by the Department's engineers should be adopted ?

(14) If, in your opinion, none of the schemes put forward by the Department's engineers indicates the best solution, what do you consider should be done, and what is your estimate of the cost of your proposals ?

Regarding the remedial measures to be taken to cure the damage and prevent further accidents, I refer to my report and to certain clauses in my replies to various points in the order of reference.

(15)–(18).

(15) Assuming you are of the opinion that the position is or can be made quite secure without moving the present power-house, do you consider that there will be any risk in proceeding to extend the power-house on the lines which were being followed prior to the trouble of the 7th June ?

(16) If your answer to No. (15) is in the negative, what additional safeguards do you consider should be provided.

(17) If your answer to No. (15) is in the affirmative, would it be practicable and safe to run the power-house up to its present installed capacity, or, alternatively, would a modification of the present installed capacity enable the present power-house to be operated with a requisite amount of safety ?

(18) If, even with additional safeguards, you are of the opinion that the present power-house should not be extended, what do you consider the best method to adopt for the generation of the remaining half of the possible power at this location ?

I consider that the position of the present power-house is quite secure, and that there is no risk in proceeding to extend the station on the lines followed prior to the occurrence on the 7th June. I therefore believe that it will be practicable and safe to run the power-house up to its present and proposed installed capacity.

(19)-(20).

(19) Having examined the geological evidence and the formation as disclosed by the test holes, do you consider that it was reasonable to erect the dam and the power-house on the sites selected ?

(20) If your answer to No. (19) is in the negative, what conclusions do you derive therefrom ?

Aside from the possibility of earthquakes and volcanic eruptions, which do not fall within the scope of my report, I believe it is quite reasonable to have erected a dam and a power-house on the sites selected.

(21) Having given full consideration to the conditions of the headrace, and in the event of your opinion precluding its further use, what alternative method would you recommend for the delivery of water to the penstocks ?

I consider that the headrace need not be abandoned, provided remedial measures as outlined in my report be taken to cure the damage and prevent further accidents.

(22)-(23).

(22) Prior to the present trouble occurring, and owing to the rapid erosion taking place below the spillway dam, authority was given to concrete the "falls." After examining the plans and specifications for this work, do you consider the proposal a proper one, possessing reasonable prospects of success, and what is your opinion of the estimated cost ?

(23) If you do not consider above proposal for concreting the "falls" a proper one, what is your alternative suggestion for dealing with this portion of the scheme and preventing further erosion ?

I consider it necessary to take measures in order to either consolidate the "falls" or hamper the speed of the destructive processes.

The proposal indicated by the Public Works Department, that aims at a consolidation of the falls, has not yet been worked out sufficiently in detail to enable an examination. It is therefore impossible to pass any definite judgment upon said project, or to compare it with any other scheme that might be conjectured.

In view of the magnitude of the works and the bearing they have on the public safety and on the successful operation of other parts of the hydro-electric plant, I cannot take it on my responsibility to present even the outlines of a project without a very careful study. This study, however, would require considerable time not only for ordinary office-work, but, very probably, even for the carrying-out of extensive hydraulic model tests.

For these reasons, and taking into account also the time that would be needed for the execution of a project of consolidating the "falls," I feel inclined to believe that no scheme of consolidation can be brought to a successful end within the time needed to bring other parts of the hydro-electric plant into working-order, which latter work should not take more than three-quarters of a year to accomplish.

Knowing that the enforced stoppage of Arapuni has caused a great scarcity of power, I have tried my best to find out whether there are any minor and less expensive means by which it might be possible to hamper the scouring processes to such a degree as to prevent them, at least temporarily, from being a menace to public safety and to the successful operation of other parts of the plant. The results of these efforts seem to a certain extent favourable, and I consider it my duty to bring them forth, because they may help to lead to a decision as to which course should be followed.

It seems, for the following reasons, likely that the breaking-down of the cliff that once formed the precipice would have been hampered if on top of the spillway channel there had been a layer preventing surface water from entering the rock.

In the joint-planes between the individual columns of the rock at the face of the "falls" the cohesive strength of the material is very small. Any alternately wet and dry surface causes the rock to "breathe," according to the saturation and evaporation, whereby a loosening of the joints, especially near the face of the cliff, may be effected.

Still greater, maybe, is the effect due to the vibrations when a thick sheet of water is rushing from the top to the bottom of the falls. It destroys whatever residium of cohesive strength there is in the joint-planes between the columns, and water runs by gravity into what have become open cracks. Eventually the cliffs break off, either column by column, or in blocks consisting of several columns.

A lining of the spillway channel, preventing water from entering open joint-planes by gravity, must hamper the process of destruction.

Still another case may be anticipated when a lining of this kind would be a means of preservation. In the bottom of the overflow channel adjacent to the face of the falls there are a number of "potholes," some of which seem to give water access to deeper strata. A source of destruction would be removed if these potholes were closed by a lining.

When the sheet of water rushes over the falls a vacuum is created behind it which tends to break off the cliff. This process of destruction would be hampered by letting in air behind the jet.

For reasons dealt with in my report regarding the damage that occurred on the 7th June, all surface cracks in the ridge between the overflow channel and the river-gorge should be grouted, and, in addition, ample drainage of all deeper cracks should be provided. Even these measures, which in my opinion will be necessary supplementary measures to any scheme aiming at a definite consolidation of the "falls," are likely to slacken the speed of the destructive processes.

All these measures, which would involve comparatively low costs, could well be executed within the time necessary to bring the other parts of the plant into working-order.

It may also be mentioned that there is a possibility that the preventive measures required might be confined to the above-mentioned limits, if the power-station is soon fully developed to its ultimate proposed capacity, and if the diversion tunnel is made more fully adequate and reliable.

24 (*a–c*).

(24) In the event of your deciding that there is no need to consider the abandonment of the scheme, are you of opinion—

(*a*) That the diversion-tunnel should be strengthened and fitted with high-velocity dispersion-type valves?
(*b*) That it should be duplicated?
(*c*) That it should be permanently concreted up?

In my opinion it is entirely out of the question to concrete-up or otherwise permanently close the diversion-tunnel. This would make the dam completely devoid of any means of lowering the water-level in the lake, should this prove desirable or necessary for inspection purposes or in emergency cases in the future.

The diversion-tunnel should be considered as an essential and integral part of the dam, and it should be treated accordingly. On the other hand, I consider it quite unnecessary to duplicate the tunnel, provided that fully adequate measures be taken to keep the present tunnel and all its appurtenances fit for their purpose.

I would not recommend that water under full pressure be let into the down-stream part of the tunnel below the cut-off wall, even if steel lining is provided. I propose, on the contrary, that the original way of operating the tunnel be maintained, and that the steel lining be postponed till it proves definitely unavoidable on account of the wearing of the concrete. In view of the experience already gained by the operation of the tunnel, this proposal does not seem to involve any risk for the public safety, and it is very unlikely that the steel lining will ever have to be put in.

The concrete lining in the tunnel has hitherto withstood the high velocities, and there is no reason why it could not, if properly mended and strengthened, endure similar conditions for shorter periods in the future, should need arise for the use of the tunnel.

It is apparent that the concrete lining in the tunnel needs repair in places. After the concrete has been repaired in places where required, the whole tunnel should be gunited. This should be done with the utmost care, by trying out a suitable mix for the gunite, and by using the very best workmanship in its application. The cover should be about $1\frac{1}{2}$ in. thick, reinforced by a wire netting, and anchored to the concrete lining by means of special anchor-bars.

Not only the tunnel, but also all its operating arrangements, should at all times be reliable. It is therefore desirable that the control gates, including groove linings, are readily accessible for inspection and repair. Due to constructional features and to the necessity of releasing water continuously to the Horahora Power-station, and also due to the character of the rock in front of the gates, it would now probably result in very considerable costs and difficulties to arrange stop-logs in front of the gates. I therefore propose that other measures for inspection and reserve purposes be taken into serious consideration—for instance, an additional gate, or a pair of gates, as near as possible down-stream of the present gates.

Costs.

It would be noticed throughout the report and this reply to the order of reference that I have done very little by way of estimating the cost of the various sections of the work. I feel that without considerably more knowledge of local conditions and prices I could not do this with any degree of accuracy. In view of the fact that I have described the works proposed in some detail, I have now no doubt but that the engineers of the Public Works Department could provide estimates with a fair degree of accuracy. Should it be possible for them to prepare preliminary estimates of the work proposed before it is necessary for me to leave New Zealand, I should be very pleased to confer with them to see that the measures I have proposed have been all provided for.

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