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M. D. Gillon
Ministry of Works and Development, Wellington, New Zealand

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M.D. Gillon
Senior Design Engineer, Ministry of Works and Development, Wellington, New Zealand

SYNOPSIS: On 2 March 1987 the 86 m high Matahina earth dam in the Eastern Bay of Plenty region of New Zealand was shaken by a nearby magnitude 6.3 earthquake. The dam response was recorded by five strong motion accelerometers and a maximum crest level acceleration of 0.42 g was measured. The crest level rockfill settled about 100 mm and moved downstream 250 mm during the earthquake. No major leakage has resulted from the earthquake.

The results of the damage investigations are described. A condition probably requiring remedial work has been identified on the left abutment.

INTRODUCTION

At 1.42pm on 2 March 1987 a shallow magnitude 6.3 earthquake occurred near the town of Edgecumbe in the eastern Bay of Plenty region of New Zealand (Figure 1). There were no fatalities, possibly because failure of electric power supply in a large foreshock forced many people outdoors. There was extensive damage to several major industrial installations and moderate damage to housing.

The Matahina earth dam and power station near Edgecumbe is owned and operated by the Electricity Corporation of New Zealand. The civil works were designed and built by the New Zealand Ministry of Works and Development who remain as consultants to the owners. The dam is located on the Rangataiki river about 23 km south of the main shock epicentre and 11 km from the main surface faulting. The intensity of shaking at the power station in the main shock was MM VII. Although initial observations did not indicate severe damage, the Matahina lake was drawn down 2.5 m as a precaution. The drawdown river flows were interpreted by residents downstream with alarm and the area was unofficially evacuated.

This paper describes the damage investigations carried out at the power station since the earthquake. These showed that crest level rockfill settlements of up to 100 mm together with a downstream movement of 250 mm had occurred during the earthquake. Crest level accelerations of 0.42 g were measured during the main shock. There has been no evidence of major leakage as a result of the earthquake. A condition probably requiring remedial work has been identified on the left abutment.

Further study of the dynamic behaviour of the dam is proposed.

REGIONAL GEOLOGY

The Matahina power station is located on the eastern margin of the Central Volcanic Region of New Zealand (Staff NZ DSIR 1987). Spreading associated with the active convergent Pacific and Australian plate boundary which lies to the east of the North Island occurs within this region. Faulting is normal and trends NE-SW. The Central Volcanic Region is a zone of young igneous rocks mainly rhyolitic and andesitic in composition. It contains recent active volcanoes and geothermal areas.

A feature of the Central Volcanic Region is extensive sheets of rhyolitic and andesitic ignimbrite. These often extend up to 50-100 km from their source with total volumes up to 200 cubic kilometres covering several thousand square kilometres (Soons and Selby 1982). The welded portion of the Matahina ignimbrite sheet forms vertical cliffs along the canyon of the Rangitaiki River in the area of the dam and lake. At the damsite it is a hard columnar jointed welded tuff.

The earthquake occurred in the extreme north east of the Central Volcanic Region under the lowlying alluvial flood plain of the Rangitaiki River (Figure 1).

To the east of the damsite and the Central Volcanic Region lie the Jurassic greywacke rocks of the Raungaehe Range (Figure 2). Several major active faults occur in this area. These faults trend N-S and are associated with the major transcurrent movements occurring within New Zealand. One of these faults, the Waiohau fault, traverses the western edge of the damsite.

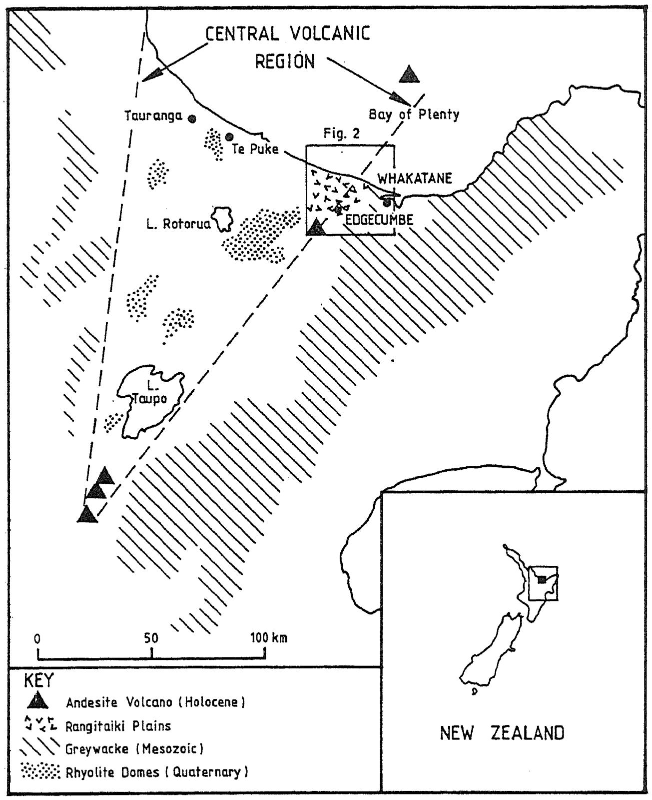

Figure 1. Location (Staff NZ DSIR, 1987)

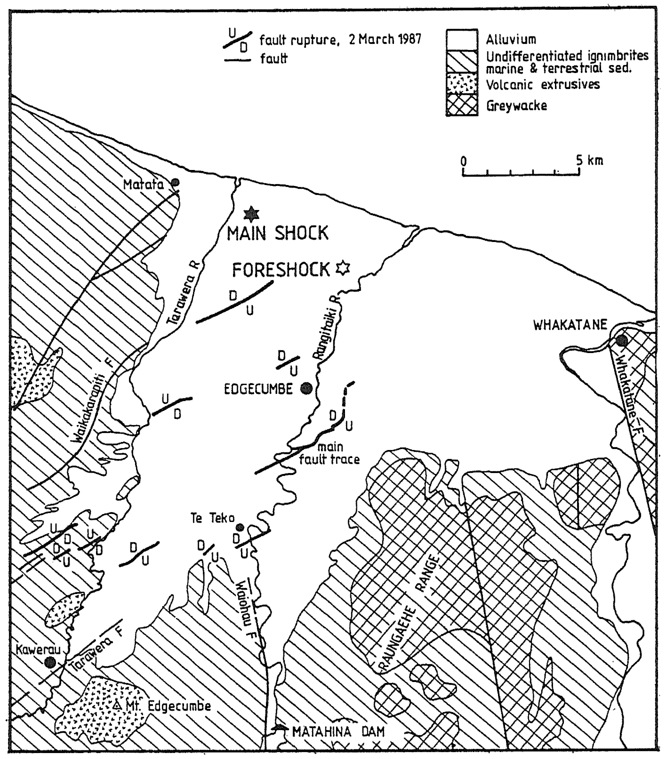

Figure 2. Geology, Epicentres, and Fault locations (Adapted from Staff NZ DSIR, 1987)

THE EDGECUMBE EARTHQUAKE

In the two weeks preceding the main event there were earthquake swarms in the region (Staff NZ DSIR 1987). These culminated in the main shock at 01h 42m 34s on 2 March 1987 UT. The epicentre location was 8 km NNW of Edgecumbe (Figure 2) and the focal depth was estimated to be 12 km. The magnitude (M_L) of the main shock was 6.3. A foreshock and four aftershocks had magnitudes of over 5.0 with epicentres within a few kilometres of the main shock.

The main surface rupture (Figure 2) occurred south of Edgecumbe and had a maximum of 2 m vertical displacement. Surface rupture and instrument records suggest normal faulting.

The accelerometer at the base of the dam recorded the M_L 5.2 foreshock, the M_L 6.3 main shock and the largest aftershock, the M_L 5.5 event 8½ minutes after the main shock. The transverse (upstream-downstream) acceleration, velocity and displacement record from the base of the dam and the 5% damped acceleration response spectra are shown in Figure 3. The El Centro 1940 (N-S) response spectra is shown for comparison.

DESCRIPTION OF DAM

At the damsite the river has cut a gorge through an extensive ignimbrite sheet into compact gravels, sands and silty clays of Tertiary age. The dam abutments are therefore hard rock underlain by compact alluvial materials at lower levels. The Waiohau fault traverses the rock of the left abutment approximately 500 m from the dam and splinter faults from this occur within the dam foundation.

The diversion and dewatering tunnels, the spillway, the penstocks and powerhouse are founded on a prominent rock spur which forms the left abutment (Figure 4). There is a grout curtain forming a partial cutoff within the spur supplemented by two drainage drives. Seepage flows and groundwater levels are monitored.

The dam (Figure 5) stands 86 m high above foundation level and has a crest length of 400 m. It has an upstream sloping core of moderate width. The core material is weathered greywacke with a low plasticity gravelly clay grading. The dam shoulders are of hard ignimbrite rockfill compacted by heavy tractor track rolling. The transition zones between the core and shoulders comprise the fines and softer strippings from the ignimbrite rockfill quarry.

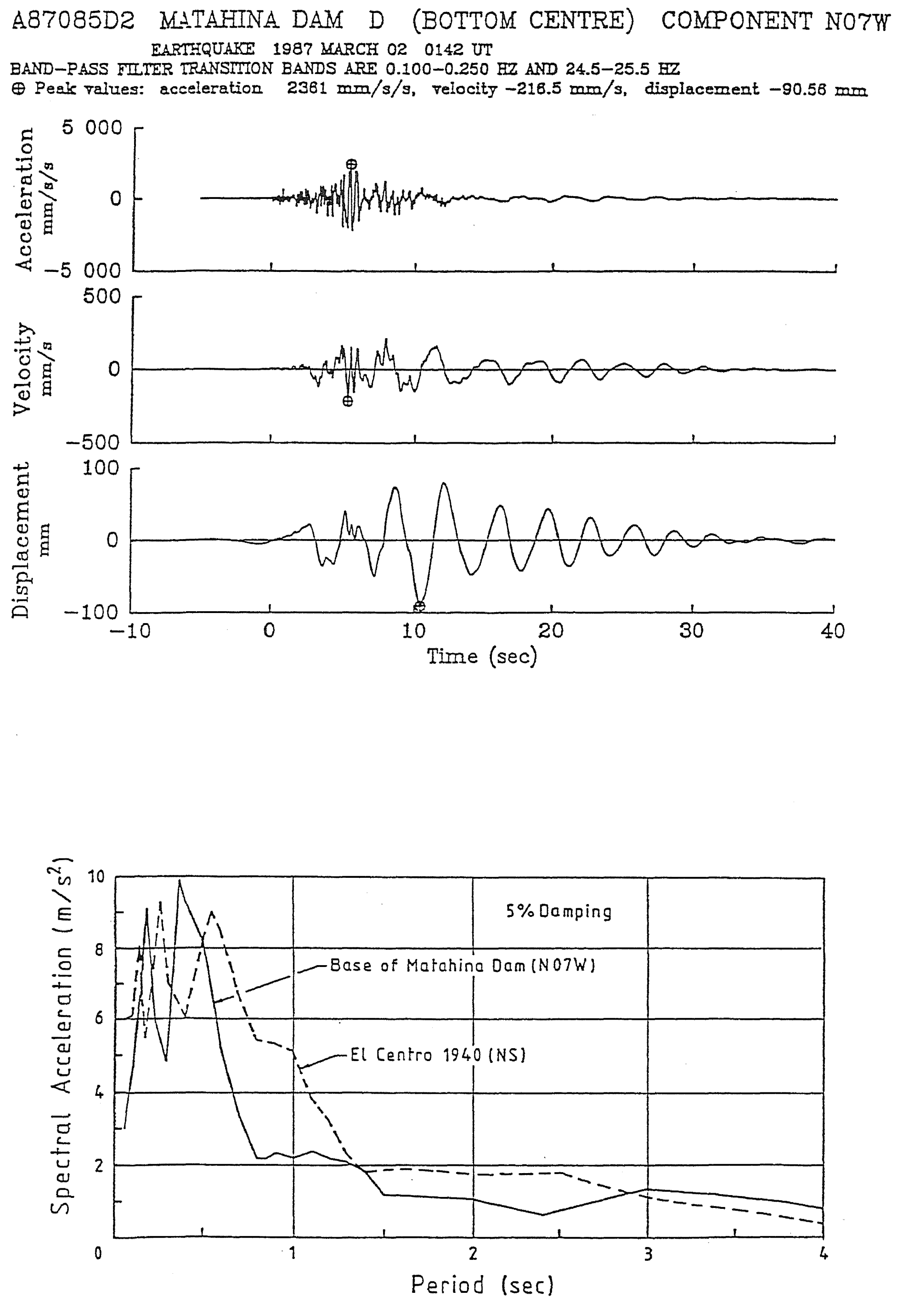

Figure 3. Acceleration, velocity and displacement at the base of the Matahina Dam and comparison of the 5% damped acceleration response spectra there with El Centro 1940 (NS).

Figure 4. Matahina Dam (D.L. Homer DSIR)

Underseepage is controlled by a shallow cutoff below the core and a 30 m deep curtain of drain holes which discharge into an extensive drainage blanket. Flow from the drainage blanket is monitored by a weir located in the old river channel downstream of the dam.

The dam instruments include five strong motion accelerometers from which records of the foreshock and mainshock were obtained. The extensive surface monument network had been resurveyed three weeks prior to the earthquake.

During lakefilling in 1967, core cracking, leakage and internal erosion occurred above a step in the right abutment (Galloway, 1967). High turbid leakage flows were observed at the drainage blanket monitoring weir. An erosion cavity was subsequently located downstream of the core. Repairs comprised a plastic concrete patch on the downstream side of the core backed by granular filter zones. The core was grouted with a cement bentonite mix and the lake refilled without further incident.

Settlement and downstream movement of the dam have continued since lake filling. The movements are consistent with the observed performance of similar dams.

POST EARTHQUAKE INSPECTION

Detailed inspection following the earthquake showed surface cracking and minor local settlements near the abutments, a turbid and increased drainage flow from the left abutment spur, a minor increase in flow at the drainage blanket weir, settlement and downstream displacement of the crest and large settlements in the upstream rockfill shoulder. The lake was drawndown to near minimum operating level as a precaution. Generation was resumed 14 hours after the earthquake.

DAMAGE INVESTIGATIONS

In view of the 1967 leakage incident, the presence of surface cracking and the considerable earthquake deformations which had occurred, the abutment areas were investigated using geophysical methods, surface trenching and air flushed drill holes.

Trenching showed the cracks to be shallow and not continuous through the core. It also revealed a large cavity beneath the roading basecourse upstream of the core on the right abutment. The location of the cavity directly upstream of the 1967 leak repair and the lack of large leakage flows at the drainage blanket weir strongly suggested that the cavity was related to the 1967 incident. It is considered that the earthquake compacted loose materials above the leakage area creating the void which was found.

As a result of surface deformation above the 1967 leakage repair two shafts were drilled to check the integrity of the repair. On the left abutment drilling showed high water inflows and this investigation was extended. Survey showed that continuing settlement of the dam and left abutment spur was occurring several weeks after the earthquakes.

During the investigations detailed monitoring was maintained. This included repeated precise level measurements, readings of selected permanent instrumentation, visual inspection and monitoring of additional investigation piezometers. The monitoring schedules were revised

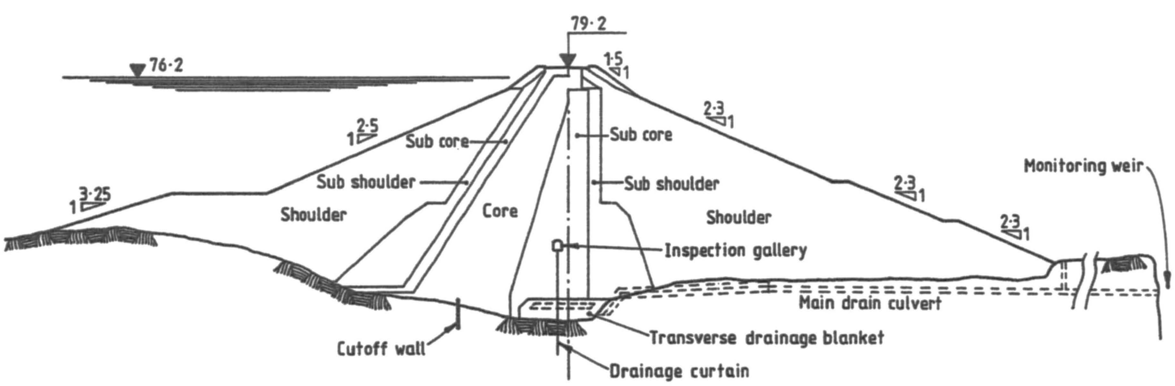

Figure 5. Cross section of the Matahina Dam.

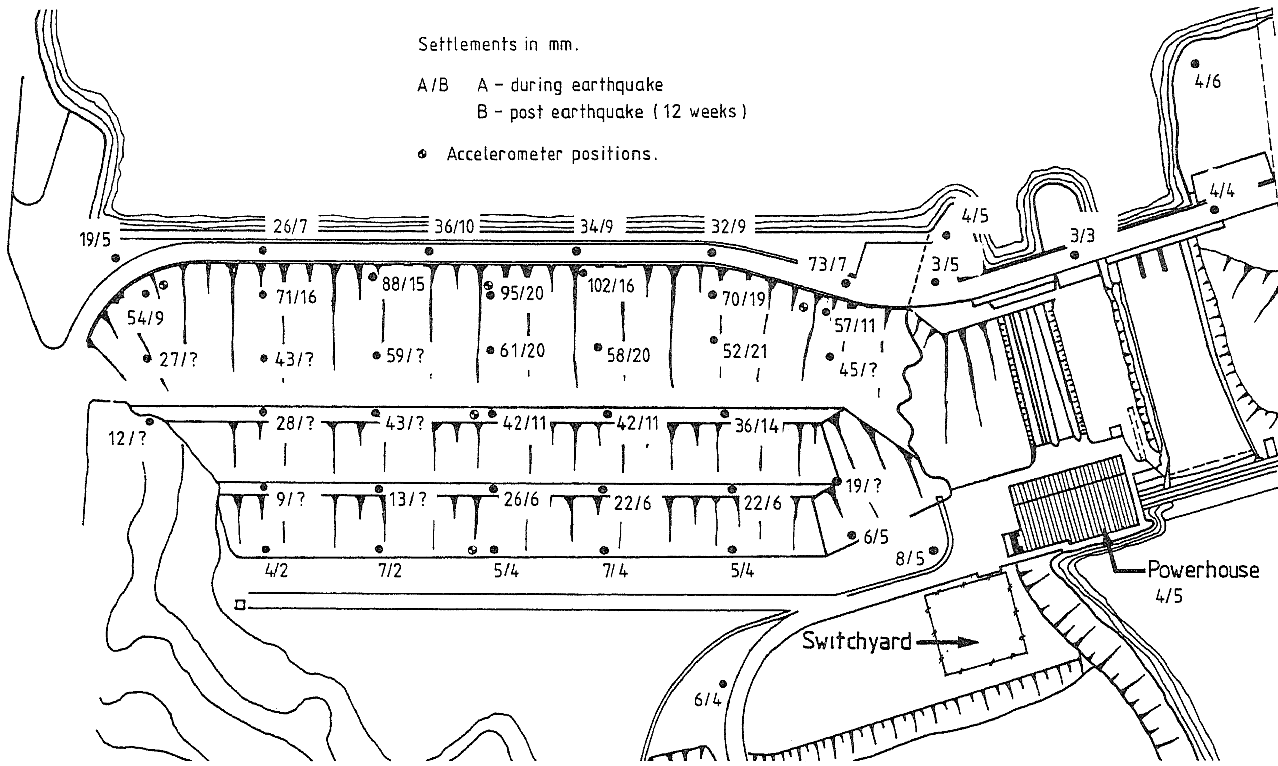

Figure 6. Settlements resulting from earthquake.

several times when conditions with possible safety implications were found. Currently the lake is held near minimum operating level with daily monitoring of selected instruments.

An alarm has been installed on the earth dam drainage blanket weir to detect abnormal flows.

INVESTIGATION RESULTS

Seepage

During the period of lake drawdown following the earthquake flow from the drainage blanket weir increased from 70 l/min to 630 l/min. Four days after the earthquake flow from the weir ceased and it has flowed only intermittently since then.

In order to interpret these observations, weir flow records were analysed with respect to lake level, tailwater level and local rainfall. While flows were clearly influenced by tailwater level and rainfall, the scatter of results inhibited interpretation. Flows of up to 350 l/min were injected into the drainage blanket without any discernible response.

The conclusions drawn from this work were that in periods of low tailwater level flow from the drainage blanket leaks into the groundwater system downstream of the dam; that the increase in flow after the earthquake was probably due to the increased tailwater level during drawdown; that increased leakage up to 2000 l/min may not be detected during periods of zero weir flow, and that no major dam leakage has occurred as a result of the earthquake.

It is proposed to undertake tracer tests in the drainage blanket when weir flow is re-established. This would assist in the estimation of total drainage flows and losses.

Seepage flow from the left abutment rock spur which rose to four times normal flow after the earthquake has continued to slowly rise after initially decreasing. This trend is being closely monitored eight months after the earthquake.

Settlements

Measured settlements of survey points are shown in Figure 6 (Currie, 1987). These show the very small settlements of the left abutment spur and the much larger settlement of the dam immediately after the earthquake. Given the level of shaking the settlements are not considered excessive but they were viewed with concern because of the core cracking and erosion associated with lake filling.

Settlement of the dam continued for several weeks. During this time the crest settlements were less than the rockfill settlements as would be expected. Measurements from the inspection gallery do not suggest significant foundation settlement (Figure 7).

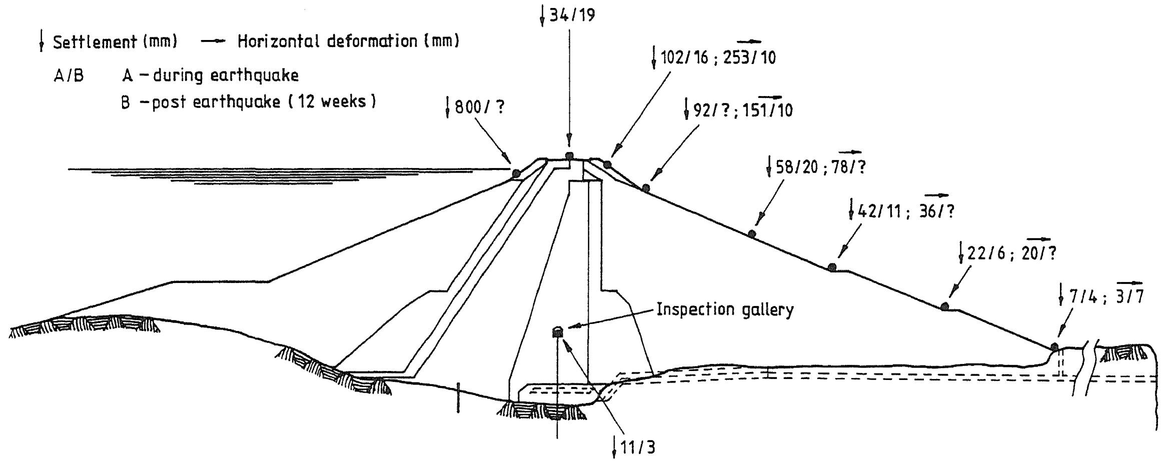

Figure 7. Deformations at centre of dam

The long term settlement of the left abutment spur was unexpected (Figure 6). The results indicate a fairly uniform settlement without tilting. The settlement caused increased leakage into the powerhouse. Initially it was suspected that the spur settlements may have been tectonic in origin but level traverses across the Waiohau fault did not support this. It is possible that the silt which is inferred to underlie the ignimbrite sheet compacted, developing excess pore pressures which took some weeks to dissipate.

The upstream shoulder settlements were estimated by levelling the colour change in the rip rap along the dam. (Normal lake level is marked by a distinct colour change). Settlements of 800 mm were typical. Subsurface sonar was used to check for evidence of underwater slope failure. There were no detectable scarps and it is considered that the settlements are simply the result of earthquake induced compaction of the rockfill.

Displacement

The displacement of the downstream rockfill shoulder is shown in Figure 7. The maximum displacement of 253 mm compares with about 220 mm during the lake filling period. The ratio of long term crest displacement/settlement (typically 2.5) is similar to that observed during the earthquake.

Right abutment leak repair area

Road seal cracking and settlement above the 1967 leak repair area was observed some weeks after the earthquake. The cracking was located above and along the step in the abutment where core erosion had occurred. SPT soundings in the repair zone and trenching observations showed that the sand filter was in a very loose state. Because of the uncertainty of leak detection from the drainage blanket weir and the possibility that the settlement and the low densities were due to leakage and material loss from the base of the repair, two cased shafts were drilled into it. These showed that the repair had not leaked significantly during the earthquake but that it had leaked soon after lake filling in 1967. The loose nature of the sand filter was satisfactorily explained by checking the construction methods with the field staff who had supervised construction.

The fact of prior leakage was established when seams of eroded core material were found in the sand filter downstream of the plastic concrete patch. The seams had formed on the surface of the jute sand bags which were used as formwork for placing the plastic concrete. This established the timing as prior to the rotting of the jute. The location of the seams suggested that leakage had occurred around rather than through the plastic concrete. The sedimentary structure within the seams was indicative of smallish rather than large leaks.

The continued presence of core defects in which erosion has occurred indicates that the remedial core grouting carried out with the repair was probably not effective. Drilling and piezometer measurements from the current investigations support this view.

It was concluded that leakage defects still exist in the repair and that they are filled with eroded core material held in place by the sand filter in the repair zone.

Left abutment area

Four inclined drill holes were drilled using air flushing. High water inflows were encountered downstream of the core. Caving areas were found in two holes. Twelve piezometers were installed and anomalously high pore pressures measured. Permeabilities measured from falling head tests in the piezometers are at least 1000 times higher than expected.

The results indicate that core cracking and erosion had occurred similar to that observed in 1967 on the right abutment. It is not known whether the defects predate or postdate the earthquake. Intensive monitoring indicates that they are stable at present. Remedial measures are proposed. The lake is being held close to minimum operating level.

DYNAMIC BEHAVIOUR

A summary of the maximum accelerations measured on the transverse dam centreline is given in Table 1. The accelerometer locations on the downstream rockfill shoulder are shown in Figure 6.

	Acceleration (mm/sec^2)		
Component	Base	Midheight	Crest
Vertical	1378	2018	2824
Horizontal			
- maximum	3247	4680	4155
- transverse	2361	4366	3427
- longitudinal	2774	3209	2766

Table 1. Maximum main shock accelerations recorded on the dam centreline (McVerry, 1987)

The vertical base acceleration is amplified by a factor of over two at crest level. The horizontal crest components are amplified more in the transverse direction than in the longitudinal direction. An unexpected result is that the highest horizontal accelerations (0.48g) are measured on the rockfill shoulder at the midheight of the dam. This aspect will be investigated further.

Analysis of the 2 March 1987 accelerograms is still in the initial stages. Fourier spectra analysis estimates (McVerry, 1987) of the transverse and longitudinal dam crest first mode period in the 2 March foreshock and main shock are given in Table 2 together with results for a small earthquake in 1977. As expected the results show a lengthening of the effective fundamental periods in the main shock compared with the two other smaller events.

Event	Maximum horizontal crest acceleration	First mode period (sec)	
		Transverse	Longitudinal
1977	0.045g	0.79	0.83
1987 Foreshock	0.054g	0.80	0.89
1987 Mainshock	0.42g	1.14	1.12

Table 2. First Mode Periods from Fourier Spectra Peaks of Dam Crest Accelerograms

Some results are available from a preliminary analysis of the dam response in the mainshock using a linear modal approach (McVerry, 1987). A systematic identification technique was used to obtain the parameters of the first few modes of the dam in the transverse and longitudinal directions which provided the best least squares fit of the recorded crest response when subjected to the recorded base acceleration in the same direction.

The non linear behaviour of the dam in the course of the mainshock made it difficult to reproduce the recorded response with a single time-invariant linear model. Excellent matches of portions of the response were obtained by analysing segments of the recorded motions.

The results for the transverse crest response (Figure 8) show that the first mode period lengthens from about 0.80 seconds in the foreshock to 1.36 seconds during the time of strongest response. The period drops to about 0.92 seconds in the decay portion of the record. First mode damping reached about 25% of critical in the largest amplitude motion dropping to about 7% in the decaying portion of the response.

The matching of response in the longitudinal direction was more difficult. First mode periods between 0.86 and 1.02 seconds were obtained for various segments. First mode damping was generally in the range of 12 to 14% of critical with one segment reaching 23%.

The results of the analysis to date show evidence of mainly hysteretic behaviour. The recovery in the decay portion of the transverse crest record (Figure 8) is reassuring but shows evidence of softening. The lack of mid crest accelerograms in the aftershocks prevents direct determination of the post earthquake first mode period. It is hoped that analysis of aftershock records from the other accelerometers will provide information on the post earthquake properties of the dam.

CONCLUSIONS

The Matahina dam experienced significant shaking in a nearby magnitude 6.3 earthquake. The downstream rockfill shoulder settled 100 mm and was displaced up to 250 mm downstream in the earthquake. The upstream rockfill shoulder settled by about 800 mm. No major leakage has been observed. Conditions requiring remedial work have been located on the left abutment but it is not known if these result from the earthquake.

The highest acceleration on the dam body during the mainshock was 0.48g measured at the midheight. The maximum crest level acceleration was 0.42g. Fourier spectral analysis of foreshock and main shock records showed a significant lengthening of the first mode period in the mainshock. A preliminary linear modal analysis of segments of the main shock transverse accelerations showed a lengthening of the first mode period during the most intense shaking with partial recovery of stiffness in the decay part of the record.

ACKNOWLEDGEMENT

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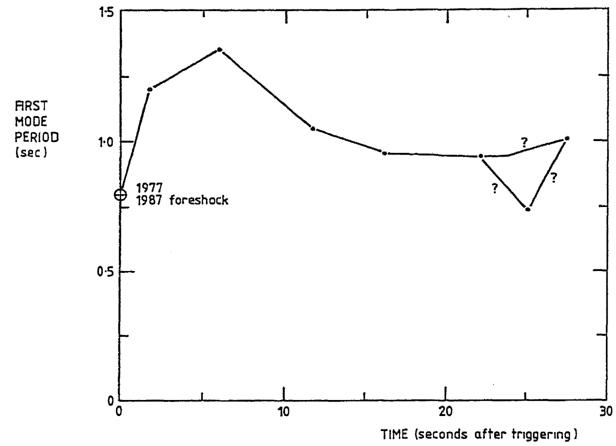

Figure 8. Variation of transverse first mode period during the mainshock (McVerry, 1987)