Development of Economical Solutions to Mitigate Geotechnical Risks: Waipaoa Water Treatment Augmentation Plant

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SUMMARY A case study of the Waipaoa Treatment Plant is presented to illustrate the use of engineering and economic evaluation to assess geotechnical and seismic risks, and develop economical solutions to civil engineering projects. At the Waipaoa Site, geotechnical assessment identified a high risk of damage to the main plant due to settlements, and a moderate risk of damage due to liquefaction during large earthquake events. An economic evaluation provided the likely financial benefits from ground improvement measures to mitigate these risks, and enabled a comparison of the capital expenditure and the likely costs during the life of the facility. This enabled the Client to decide on the level of risk mitigation appropriate for the facility, and provided a basis for the design of the treatment plant and ground improvement measures.

1. INTRODUCTION

Recent advances in geotechnical and seismic engineering enable engineers to identify and develop solutions to mitigate risks which were previously considered unavoidable. However these risks, particularly geotechnical seismic risks are difficult to assess with any certainty, and may involve expensive engineering solutions. Therefore, engineers and clients require some method of deciding on the level of risk mitigation appropriate for their particular project.

This paper illustrates the use of recent developments in geotechnical and seismic engineering, and economic evaluation to provide a basis for clients to decide on the level of risk mitigation appropriate for their facility. This can then be used to develop solutions which are sound, cost effective and commercially viable.

The Waipaoa water treatment augmentation plant is located on the east bank of Waipaoa River, about 10 km northwest of Gisborne City in New Zealand, and will augment the water supply to Gisborne particularly during the drier summer months. The plant consists of a river intake sump, presedimentation ponds, and the main plant. The main plant includes clarifiers, filters, a clear water tank and an operations building, see Figure 1.

It's location on alluvial deposits generally comprising of loose silty sand to soft silty clay makes the facility susceptible to large settlements and earthquake induced liquefaction. The assessment of settlement and liquefaction risks, development of engineering solutions to mitigate these risks, and the use of economic evaluation to select economically viable solutions are presented.

2. GROUND CONDITIONS

Ground investigations comprising boreholes and Static Cone Penetration Tests (CPT) were carried out followed by laboratory soil classification tests, and one dimensional consolidation tests.

In the presedimentation pond area, the soils are predominantly loose silty sands to a depth of about 12 m, with soft clayey silts below this depth. Standard Penetration Test (SPT) N-values vary from about 3 at 2 m depth, increasing to about 10 at 25 m depth. Groundwater levels were 2 m to 5 m below surface during the investigations in the summer.

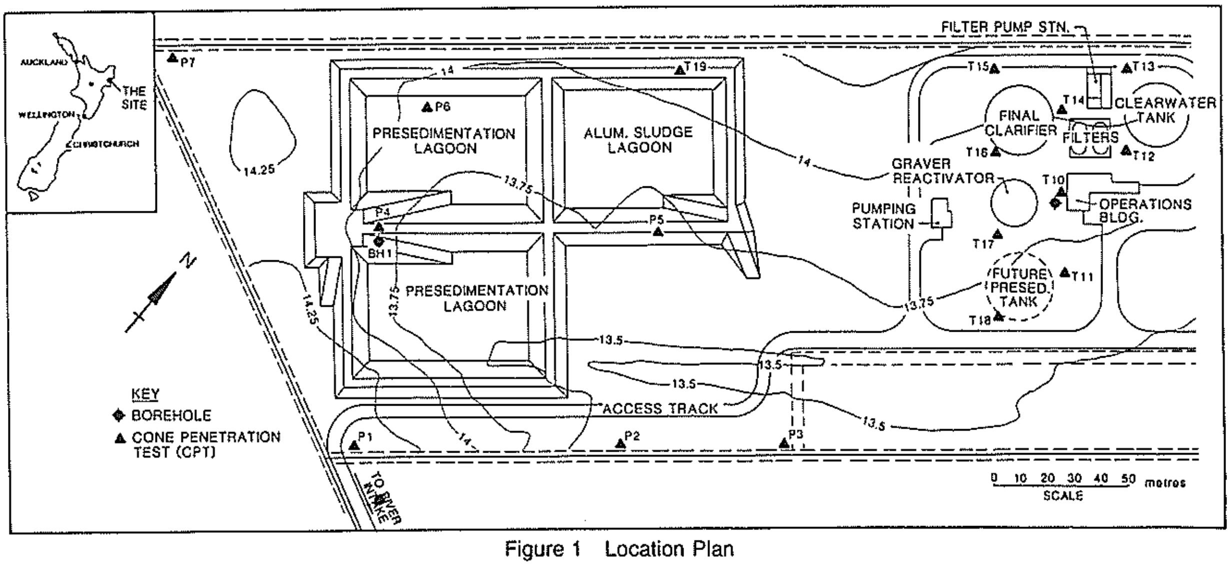

Figure 1 Location Plan

Figure 2 shows the ground conditions at the main plant area, where the soils are more fine grained than at the presedimentation pond site. The soils are predominantly soft clayey and sandy silts to a depth of about 12 m, below which the soils become silty clay and clayey silt. There are a number of silty sand horizons which are continuous over the site. SPT N-values vary from about 2 near the ground surface to about 10 at 25 m depth. CPT cone resistance (q_c) values vary from about 0.3 MPa at 3 m depth increasing to about 1.2 MPa at 30 m depth. The groundwater levels at the main plant area vary between about 0 m and 3 m below ground surface.

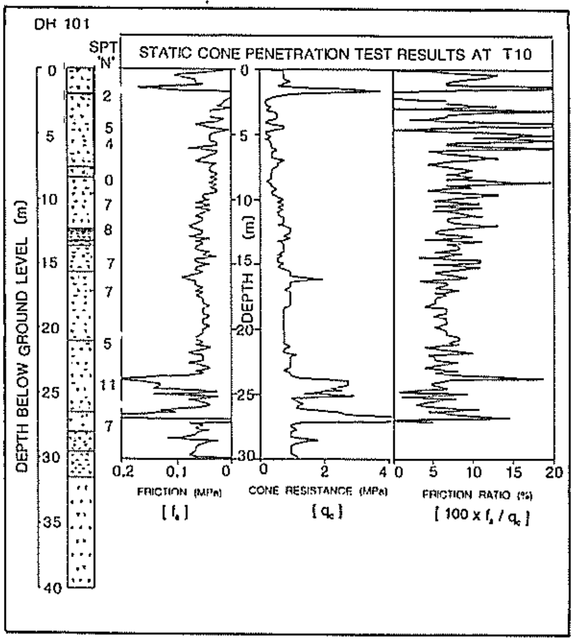

Figure 2 Ground Conditions at Waipaoa Main Plant Area

3. SEISMICITY

Waipaoa is situated in a region of New Zealand with high seismic risk. The return periods, magnitudes and peak ground accelerations for earthquakes of Modified Mercalli intensities ranging from VI to X have been estimated from Matuschka (1980), Smith and Berryman (1986), and Smith (1990), and are shown in Table I.

TABLE I
SEISMICITY OF THE WAIPAOA SITE

RETURN PERIOD (YEARS)	INTENSITY (MODIFIED MERCALLI)	MAGNITUDE (RICHTER)	PEAK GROUND ACCELERATION
9	VI	6.5	0.14 g
45	VII	7.0	0.21 g
140	VIII	7.5	0.31 g
410	IX	8.0	0.46 g
1729	X	8.5	> 0.5 g

4. SETTLEMENTS

The geotechnical investigations showed the soils at the Waipaoa site to be compressible. Six consolidation tests carried out on soils recovered during drilling gave coefficients of volume compressibility (m_v) ranging from about 0.33 m^2/MN near ground surface to about 0.15 m^2/MN at 35 m depth.

The coefficient of secondary compression (C_α) assessed from the consolidation tests is about 0.0022. The soils at Waipaoa site are of medium to high compressibility and extend to depths exceeding 40 m, giving a potential for large settlements of the treatment plant structures under their imposed loads.

In the main plant area, the tanks are partially set into the ground, to reduce the net bearing pressure on the ground. Primary consolidation settlements of up to 200 mm and secondary compression settlements of up to 150 mm were estimated for the 18 m to 25 m diameter main plant tanks. These could result in differential settlements of the order of 150 mm across or between the tanks.

In view of the high compressibility of the soils, the presedimentation ponds were designed with earth bunds which are more flexible than concrete or steel structures. The ponds are also partially set into the ground to minimise the net bearing pressures and hence the settlements.

5. LIQUEFACTION

The Waipaoa site is susceptible to liquefaction, because it has high groundwater levels, loose sandy silt/silty sand, and potential for large earthquake events. The particle size distribution of the soils at the Waipaoa Site is shown on Figure 3, together with the grading envelopes for soils which liquefy (Tsuchida, 1971). The particle size distribution of the soils from Waipaoa range from soils which "very easily liquefy" to soils which are finer than those considered to liquefy (Tsuchida, 1971). Recent research has indicated that liquefaction of soils with a significant silt content can occur, although these were previously considered resistant to liquefaction.

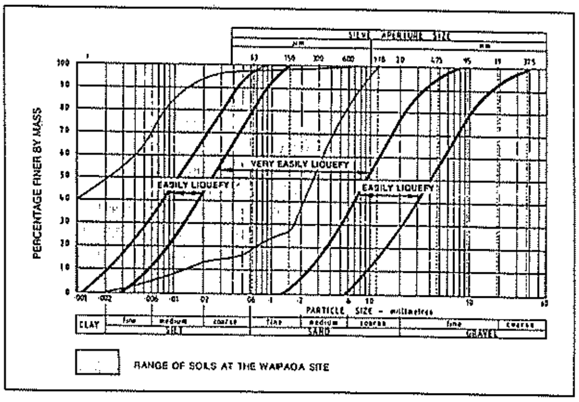

Figure 3 Particle Size Distribution of Waipaoa Soils

Seed et al (1984) have developed an empirical correlation to assess the liquefaction susceptibility of soils with fines. The fines content is defined as the total percentage of silt and clay size particles. Figure 4 shows the intensity of ground motion at the site represented by the stress ratio [τ_{av}/σ'_0] against the corrected SPT N-value for the Waipaoa site, where τ_{av} is the average peak shear stress and σ'_0 is the effective overburden stress evaluated at a depth under consideration. The figure shows the stress ratio for an earthquake event giving a peak ground acceleration of 0.24 g and the corrected SPT N-value for the Waipaoa site in comparison with the empirical criteria for liquefaction presented by Seed et al.(1984). This comparison shows that the soils at Waipaoa are susceptible to liquefaction.

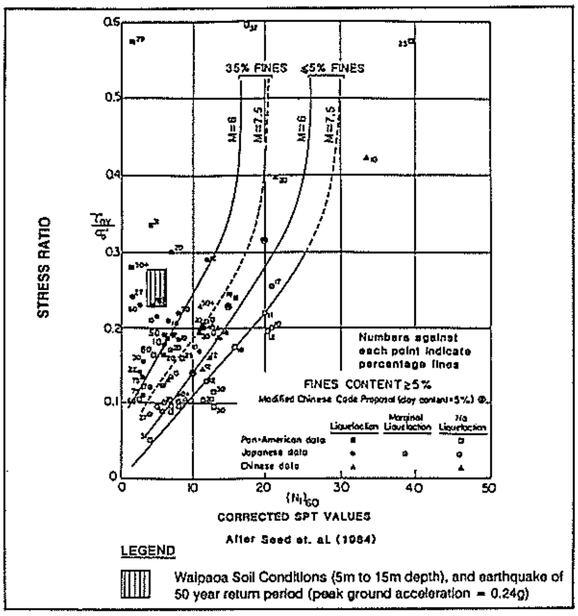

Figure 4 Liquefaction from Stress Ratio-SPT Relationship

Arulanandan et al (1986) have presented information on soils in Ying Kou City in China that liquefied and gave surface expression during the Magnitude 7.3 (Richter) Haicheng earthquake in 1975. The Ying Kou City experience shows that even soils with 40% to 90 % fines which have low SPT N-values can liquefy. Table II shows a comparison of the soil properties and the potential seismic events at Waipaoa, with the soil properties in Ying Kou City and the 1975 Haicheng earthquake. The soils at both sites have large moisture contents and liquidity indices, indicating a loose soil structure. The comparison shows remarkable similarities between the two sites, suggesting the soils at Waipaoa to be susceptible to liquefaction.

TABLE II
PARAMETERS INFLUENCING LIQUEFACTION AT YING KOU CITY AND WAIPAOA SITES

PARAMETER INFLUENCING LIQUEFACTION	YING KOU CITY 1975 HAICHENG EARTHQUAKE	WAIPAOA SITE
Earthquake - magnitude - ground acceleration	 7.3 0.1 - 0.15 g	 up to 8 up to 0.55 g
Groundwater - depth below ground level	1 - 2 m	0 - 3 m
Moisture Content	24 - 35%	22 - 42%
Fines Content	40 - 90%	5 - 90%
Plasticity Index	6 - 14	9 - 27
Liquidity Index	0.5 - 2.3	0.3 - 1.5
SPT 'N' (weak layers)	3 - 5	0 - 7
Cone Resistance q_c	0.3 - 5.9 MPa	0.2 - 1.2 MPa

The Waipaoa site has the conditions necessary for liquefaction, and empirical correlations reported in the research literature indicate the soils at Waipaoa to be susceptible to liquefaction, although they have a high percentage of fines. The soils will actually liquefy only if sufficient porewater pressures can develop during a seismic event.

Dynamic triaxial tests on samples of sand and silt from the Waipaoa main plant site was carried out at different stress ratios, to directly assess their susceptibility to pore pressure development, and hence liquefaction. There is insufficient test data to define the relationship between the stress ratio and the number of cycles of dynamic excitation for initial liquefaction. However, an assessment using the trend from research literature (National Research Council, 1985) and the laboratory test data show that earthquake events giving a peak ground acceleration of about 0.24 g or more could cause liquefaction at the Waipaoa main plant site.

The consequences of liquefaction are important in assessing the potential loss due to damage caused by an earthquake event. At the Waipaoa main plant site, liquefaction could cause loss of bearing capacity resulting in tilting of the tanks, or settlements of the order of 400 mm which can cause significant damage. The partially buried tanks proposed could float out of the ground when the surrounding ground liquefies, causing significant damage similar to that observed in Whakatane during the 1988 Edgecumbe earthquake in New Zealand (Jennings et al, 1988).

6. RISK MITIGATION

To reduce the risk of damage to the treatment plant due to settlements caused by compression of the soils, and earthquake induced liquefaction, special foundation measures or treatment were considered to be necessary. The structures could have been founded on deep pile foundations bearing on an unliquefiable dense stratum of low compressibility. However, as the soft to firm and compressible soils extend to a depth more than 40 m, piles would have been long making the piled foundation option expensive. Ground improvement could be used to mitigate the risk. Two methods, preloading and dynamic compaction were considered to provide the most practical and effective solutions at a reasonable cost.

Preloading the site with a 4 m high earthfill embankment for a period of about six months would reduce post-construction settlements to an acceptable level and reduce the risk of settlement damage. However, preloading would not appreciably reduce the risk of damage due to liquefaction. Dynamic compaction would reduce the liquefaction susceptibility of the soils, and thus mitigate the risk of damage due to earthquake events. It could also reduce the compressibility of the soils to a maximum depth of 15 m. Since the tanks at Waipaoa are up to 25 m diameter, their depth of influence is much greater than 15 m. Therefore, dynamic compaction alone would not sufficiently reduce the risk of settlement damage. A combination of dynamic compaction and preloading would minimise the risk of damage due to settlements and earthquake induced liquefaction.

7. ECONOMIC ANALYSIS

An economic analysis of financial benefits from risk mitigation measures for the Waipaoa Treatment Plant was carried out. The value of the treatment plant and the cost of ground improvement for risk mitigation is shown on Table III.

7.1 Presedimentation Ponds

For the presedimentation ponds, the cost of risk mitigation measures is $ 0.42 million for dynamic compaction of the soils, and $ 0.25 million for preloading the area. The total cost of $ 0.67 million is very high compared to the $ 0.8 million value of the ponds. This clearly shows that ground improvement would be uneconomical for the presedimentation ponds, and a detailed economic analysis was not necessary. It was therefore decided to design the ponds to minimise damage rather than carry out expensive ground improvement.

TABLE III
COST OF RISK MITIGATION OPTIONS

TREATMENT PLANT COMPONENT	VALUE OF SCHEME	COST OF RISK MITIGATION BY GROUND IMPROVEMENT		
		PRELOADING	DYNAMIC COMPACTION	PRELOADING AND DYNAMIC COMPACTION
	$ MILLION			
Main Treatment Plant	6.0	0.28	0.32	0.60
Presedimentation Ponds	0.8	0.25	0.42	0.67

7.2 Main Plant

The value of the Main Plant structures is $ 6 million, and the cost of ground improvement by preloading and by dynamic compaction are $ 0.28 million and $ 0.32 million respectively. A detailed economic analysis was considered appropriate to assess the economic benefits from ground improvement. The aim of the economic analysis is to determine the optimum level of risk mitigation. Ground improvement is not economically prudent unless the expected reduction in damages exceed the actual cost of carrying out the improvement.

7.2.1 Settlement damage

Without ground improvement, settlement of the treatment plant would certainly have occurred. However, there is a probability associated with settlement damage, due to the uncertainties in the assessment of the amount of settlement. This probability together with the assessed cost of reinstating the structures damaged due to settlement, was used to assess the total damage cost if no ground improvement was undertaken. Similarly, the damage cost with each option was calculated assuming the reduction in settlement likely to be achieved, and the probability of the ground improvement being effective.

It was considered likely that most of the damage to the treatment plant due to settlement of the structures would occur during the first year after construction, because the presence of laterally extensive sand layers would assist drainage and accelerate consolidation.

7.2.2 Seismic damage

The expected cost of damage can be estimated from the integral of the Damage cost v Probability of occurrence curve (Ministry of Works and Development, 1983). For seismic induced damage from ground shaking and liquefaction, this curve can be derived by combining the probability of occurrence and the expected damage costs for seismic events of different intensities, as illustrated in Figure 5.

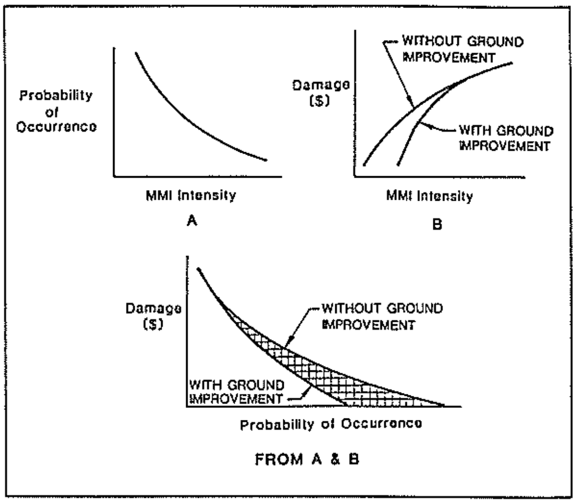

Figure 5 Derivation of Seismic Damage Costs

The expected saving in damage cost resulting from ground improvement is given by the cross hatched area between the curves representing the damage costs, with and without ground improvement. The expected savings in damage costs (given by the annual damage costs discounted over the life of the facility) was then compared with the cost of the ground improvement to ascertain the economic benefits from varying levels of risk mitigation.

For the Waipaoa treatment plant, the expected damage costs were estimated from the probability of damage and the damage ratios estimated generally in accordance with the recommendations of the Applied Technology Council (1985). The damage ratio is the cost of damage as a ratio of the value of a structure. The probability of damage was assessed using the geotechnical assessments, and engineering judgement. Whilst this is not an accurate assessment, the results give sufficient accuracy to make decisions on the appropriate level of risk mitigation. The damage ratios for seismic induced liquefaction damage estimated for the Main Plant area at Waipaoa are shown in Table IV.

The estimated damage ratios together with the value of the main plant give the damage costs for various levels of seismic events. Similarly, the estimated damage costs can also be estimated assuming that ground improvement is carried out.

7.2.3 Discussion

The present value of the savings in damage costs for the different ground improvement options were calculated as discussed above, and are given in Table V.

TABLE IV
DAMAGE RATIOS FOR SEISMIC EVENTS WITH AND WITHOUT GROUND IMPROVEMENT

SEISMIC EVENT			DAMAGE RATIO (MAIN PLANT)			
MODIFIED MERCALLI INTENSITY	RETURN PERIOD (YEARS)	PROBABILITY OF EVENT/ YEAR	NO GROUND IMPROVEMENT	PRELOADING	DYNAMIC COMPACTION	PRELOADING AND DYNAMIC COMPACTION
VI	9	0.1111	-	-	-	-
VII	45	0.0222	0.15	0.10	0.03	0.03
VIII	140	0.0071	0.35	0.30	0.1	0.1
IX	410	0.0024	0.55	0.50	0.3	0.3
X	1729	0.0006	0.8	0.75	0.5	0.5
>X	-	-	1.0	1.0	1.0	1.0

TABLE V
PRESENT VALUE OF DAMAGE COST AND SAVINGS FROM GROUND IMPROVEMENT OPTIONS

OPTION	DAMAGE COST		TOTAL DAMAGE COST	SAVINGS IN DAMAGE COST
	SETTLEMENT	SEISMIC		
	$ MILLION			
No Ground Improvement	1.40	0.72	2.12	-
Preloading	0.30	0.56	0.86	1.26
Dynamic Compaction	0.75	0.21	0.96	1.16
Preloading & Dynamic Compaction	0.23	0.21	0.44	1.68

This table shows the cost of damage from settlements and from seismic events, the total damage costs and the savings in damage costs which could be achieved by different ground improvement options. Table VI shows a comparison of the savings in the total cost of damage from settlements and seismic events with the actual cost of undertaking the ground improvement measures to mitigate the risk. The benefit cost ratios for these options are also given in the table.

TABLE VI
BENEFIT / COST RATIO OF GROUND IMPROVEMENT

	COST OF RISK MITIGATION	SAVINGS IN DAMAGE COST	BENEFIT /COST RATIO	INCREMENTAL BENEFIT/COST RATIO FOR MITIGATION IN ADDITION TO PRELOADING
	$ MILLION			
Preloading	0.28	1.26	4.5	-
Dynamic Compaction	0.32	1.16	3.6	-
Preloading & Dynamic Compaction	0.60	1.68	2.8	1.3

For the main plant area, potentially large savings in damage costs can be achieved through ground improvement. By preloading the site to reduce settlement damage, a reduction in damage costs of about $ 1.26 million can be expected for an initial remedial works cost of $ 0.28 million, representing a benefit / cost ratio of 4.5, see Table VI. While dynamic compaction also offers a good overall benefit for the cost of the work, it actually offers less benefit at a higher initial cost compared to preloading.

The combined option of using both preloading and dynamic compaction would reduce the risk of both settlement damage and liquefaction damage giving potential savings of $ 1.68 million for an initial mitigation cost of $ 0.6 million. This gives a benefit / cost ratio of 2.8 which is a good return on investment. However, the incremental cost of $ 0.32 million over the cost of preloading, nets savings in damage costs of only about $ 0.42 million representing an incremental benefit / cost ratio of 1.3. There is a possibility that a damaging earthquake may never occur during the life of the plant. Therefore given the low incremental benefit / cost ratio and the uncertainty of ever achieving the savings in damage costs, it is difficult to justify additional expenditure on risk mitigation by dynamic compaction.

It should be noted that the client is building the Waipaoa water treatment augmentation plant only to supplement the water supply to Gisborne City during the dry summer months. Therefore, no account was taken in the economic analysis of the disruption to the water supply to Gisborne City as a result of any damage which will put the treatment plant out of operation. Further, since the failures would not be catastrophic, it is unlikely that there would be any risk to human life. If there was a risk to human life, then economical considerations may be outweighed by the need to save lives.

8. DESIGN ADOPTED

On the basis of the economic analysis, the client decided to reduce the risk of damage due to settlements by preloading the main plant site, and accept the risk of liquefaction induced damage. Also since the capital cost of the presedimentation ponds is small in comparison to the cost of risk mitigation, the Client decided not to carry out ground improvement at the presedimentation ponds site.

Preloading of the main plant area has been successfully carried out, and construction of the main treatment plant is currently underway.

9. CONCLUSIONS

The Waipaoa site is a difficult construction site with deep alluvial deposits comprising soft silts and loose sand layers, with high groundwater levels. The site investigations at an early stage showed that the ground conditions were poor and there was a risk of damaging settlements and earthquake induced liquefaction. The likely settlements were estimated based on information from the investigations. Since the soils contained fine grained silts, the risk of liquefaction was not clear and required special laboratory tests and a detailed geotechnical assessment using information from recent research literature. This enabled the risk of liquefaction to be assessed. Risk mitigation measures were chosen based on the information from the geotechnical appraisal.

The economic analysis enabled an assessment of the financial benefits from the risk mitigation measures. This gave a clear basis on which the Client made an informed judgement as to the level of risk mitigation to be adopted for the project. This method can be applied to any project, although it is recognised that additional factors such as risk to life and disruption may need to be considered in addition to the economic benefits from reduced structural damage.

10. ACKNOWLEDGEMENTS

The authors wish to acknowledge the permission to publish this paper from the Gisborne District Council for whom the work was carried out. The contribution and assistance of many colleagues in Works Consultancy Services Limited who worked on the Waipaoa project is also acknowledged.

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