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Field Testing of Crushed Ignimbrite for Seismic Retrofit Of Matahina Dam

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ABSTRACT

The performance of zoned embankment dams depends on the ability of filter and drain zones to prevent seepage erosion and piping of impervious materials, while providing adequate internal drainage. Because cracking of filter and drain zones might compromise their function, special care is typically exercised to build such zones of cohesionless materials that are unable to support cracks. Limited information is available on the cracking susceptibility of filter and drain materials manufactured by rock crushing. This paper presents a case history of field and laboratory testing of a crushed ignimbrite rock to evaluate its suitability as filter and drain material for the seismic retrofit of Matahina Dam to withstand foundation fault rupture. The paper presents the field and laboratory test results, and discusses key issues associated with the design of filters to mitigate the risk of dam cracking.

INTRODUCTION

The long-term and seismic performance of zoned embankment dams depends on the ability of filter and drain zones to prevent migration of impervious materials from leading to internal erosion and piping, while providing adequate drainage of seepage flows. Where cracking of a dam and its impervious core might occur as a result of static or seismic deformations, the ability of filter and drain materials to deform without sustaining cracks is a critical characteristic of such materials. Because cracking of filter and drain zones could compromise the filter retention function of those zones, special care is typically exercised in the design and construction of dams to use cohesionless materials for those zones.

Considerable guidance is available in the technical literature for laboratory testing of soils to evaluate their strength properties and tendency to exhibit 'apparent cohesion'. However, limited information is readily available on the cracking susceptibility of filter and drain materials in the field, particularly those manufactured by rock crushing.

This paper presents a case history of field and laboratory testing of a crushed ignimbrite rock to evaluate its suitability for use as filter and drain material for the seismic strengthening of the Matahina Dam in New Zealand, which was recently retrofitted to withstand foundation fault rupture. The test program included field tests of the materials' tendency to exhibit 'apparent cohesion' and to support open cracks and cavities. The paper describes the field tests and discusses the key issues associated with the design of filters to mitigate the risk of cracking in dams. Additional details on the test program are presented by Woodward-Clyde Consultants (1996).

MATAHINA DAM

Matahina dam is an 82-m-high, 400-m-long, zoned rockfill embankment with a sloping earth core located on the Rangitaiki River in the North Island of New Zealand. The dam was recently retrofitted to accommodate potential surface fault displacement of up to 2.7 m in its foundation by reinforcing the embankment with a downstream leakage-resistant buttress (Mejia et al., 1999). The concept behind the buttress is to prevent internal erosion of the core from leading to failure of the dam by piping or collapse of the dam crest and overtopping. The buttress incorporates a filter, transition and drain zones, and an enlarged rockfill shell. The filter is designed to arrest migration of the core, and to limit flows through the buttress even if the core is breached.

To prevent piping through the foundation, the filter and transition zones were extended to rock in a cutoff trench through the alluvium. To provide an adequate margin against shearing of the filter, transitions, and drain, the minimum horizontal and vertical dimensions of those zones were set at twice the corresponding components of the design fault displacement.

Cohesionless materials that will not sustain an open crack, and will run into any cavities that develop due to the fault displacements, were specified for the filter and transition zones. Because river-run sands and gravels were not available within economical distances, the filter and transition materials were obtained by crushing locally available hard ignimbrite rock. In view of the lack of precedent and experience with the use of crushed ignimbrite as dam filter material, a field and laboratory test program was undertaken to confirm that the crushed rock materials would not sustain open cracks. In addition, special provisions were included in the specifications to ensure that this and other desired material characteristics were obtained during construction.

IGNIMBRITE ROCK

The ignimbrite originated as a massive pyroclastic flow of hot gas and ash (tephra) from a large regional volcanic explosion in the North Island of New Zealand about 280,000 years ago. The volcanic ash, a mixture of glass shards and pumice and crystal fragments, solidified into a welded tuff after deposition. Upon cooling, the formation developed sub-vertical, columnar and sub-horizontal jointing that gives the rock a blocky appearance, with an approximate 1-m block size.

A strong, hard, welded lenticulite, the rock has an average unconfined compressive strength of about 70 MPa when tested in an air-dry condition, and about 50 MPa when tested after saturation. Based on a limited number of tests, the rock appears to be slightly weaker when loaded along the orientation of the lenticles. Its measured specific gravity ranges from 2.45 to 2.49 with an average value of about 2.47. Measured absorption values were about 4% for sand-size particles and about 3.2% for gravel-size rock.

In 45 years since the dam's construction, the hard ignimbrite blocks used for the dam rockfill shells have deteriorated little. Likewise, tall vertical faces left in the construction quarry near the dam's left abutment still stand, with minimal erosion or weathering.

TEST PROGRAM

The test program began with a test blast that generated about 1,000 m^3 of hard ignimbrite rock from one of the walls of the former construction quarry. A mobile crushing plant was set up on the quarry floor, and produced about 220 m^3 and 250 m^3 of filter and transition zone materials, respectively. The processed materials were then used to build two test embankments, one for each material. The embankments were thoroughly sampled and tested during and after construction. Pipe-pullout and trenching tests were performed in the completed test fills, and various laboratory tests were performed to supplement the field tests.

MATERIALS

Filter

A coarse to medium sand of suitable durability was used for the filter zone. Figure 1 shows the range of gradations obtained for the material from the crushing plant. The fraction of flat and elongated particles in the material was less than 1% indicating equidimensional, yet angular particles. The durability characteristics and minimum and maximum densities of the material are listed in Table 1. Slight particle breakdown occurred in the material during the laboratory compaction test, and the maximum density obtained in that test was slightly larger than that from the relative density test (Table 1).

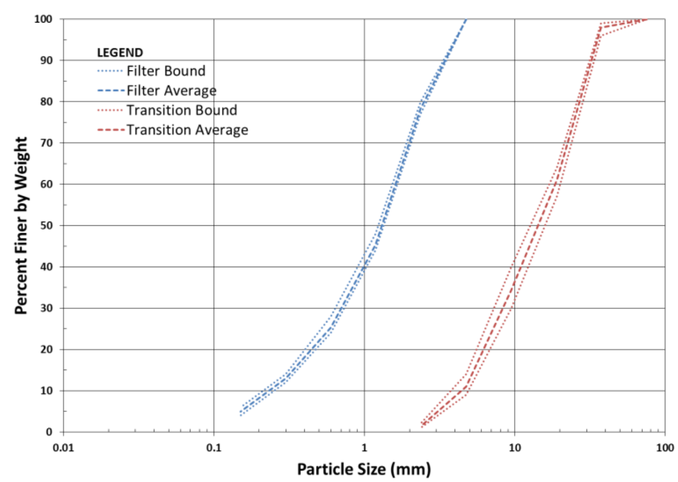


Fig. 1. Gradations of filter and transition materials in the stockpiles

Five consolidated-isotropically-undrained (CIU) triaxial compression tests and three consolidated-drained (CD) tests were performed on samples reconstituted to relative densities of about 60 to 75% at water contents of about 10%. The strength envelope parameters derived from the tests are summarized in Table 2. Three unconfined compression tests were performed on samples compacted to a relative density of about 75% and a water content of about 17%. The measured unconfined compression strength fell within a narrow range and averaged about 5 kPa at a failure axial strain of approximately 0.1%. Four constant head tests yielded permeability values ranging from 1.7 to 2.5 x 10^2 with an average of about 2 x 10^{-2} cm/s.

Table 1. Summary of Material Characteristics

Material Characteristic (ASTM Std.)	Filter Material	Transition Material
Abrasion Resistance (C131, C535) 100 Revs 500 Revs 1000 Revs	 6% Loss 18% Loss NA	 NA NA 20% Loss
Sulphate Soundness (C88)	4.8% Loss	7.4% Loss
Relative Density (D4253, 4254) Maximum Density Minimum Density	 1710 kg/m^3 1380 kg/m^3	 1540 kg/m^3 1340 kg/m^3
Laboratory Compaction (D1557) Maximum Density Optimum Water Content[1]	 1770 kg/m^3 16%	 1670 kg/m^3 -[1]
Notes: [1] Test results did not define an optimum water content		

Table 2. Effective Stress Strength Parameters of Filter Material

Test Type	Confining Stress[1] Range (kPa)	Strength Parameters	
		c' (kPa)	φ' (°)
CD[2]	15 - 45	10	45
CIU[3]	100 - 1200	31	41
Notes: [1] All-around consolidation stress; [2] Consolidated-drained triaxial compression; [3] Consolidated-isotropically-unconsolidated triaxial compression			

Transition

The transition material was a durable, coarse to medium gravel with less than 15% of flat and elongated particles. The gradation range of the materials produced by the crushing plant is shown on Figure 1. Particle shape tests revealed sub-angular fragments and a fraction of flat and elongated particles less than 6%. Table 1 lists the durability characteristics and the minimum and maximum densities of the material. The maximum density obtained in the laboratory compaction test was significantly larger than that obtained in the relative density test due to particle breakdown, which was characterized by an increase from about 5% to 15% in the amount of material passing the No. 8 sieve.

EMBANKMENT CONSTRUCTION

As shown in Figure 2, the test embankments were rectangular in plan with top dimensions of 5 m by 12 m. They were constructed with a front-end loader in 5 layers, each spread with a grader and hand-held screeds to a loose lift thickness of 300 mm. Except for the first layer, the layers were compacted in two lanes (Figure 2) with a 6-ton Sakai SV91D vibratory roller and a 10-ton Dynapac CA511PD vibratory roller operated at a low centrifugal force setting. In both embankments, layer 1 was compacted with 4 passes of the 6-ton roller on a high centrifugal force setting. A water tanker was used to wet the materials before compaction. A testing and sampling survey grid was established on each embankment with gridlines spaced at 1 m centers in the longitudinal and transverse directions (lines A through F, and 1 through 13, in Figure 2).

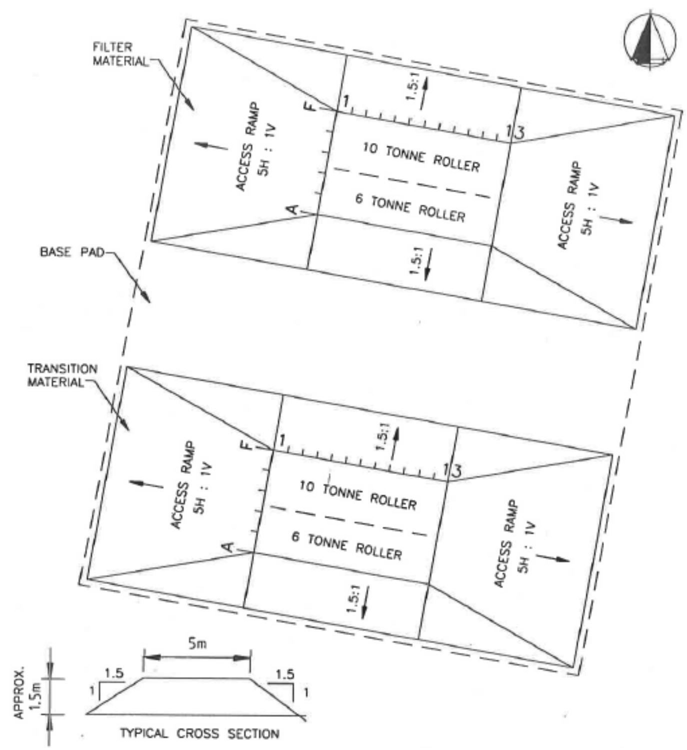
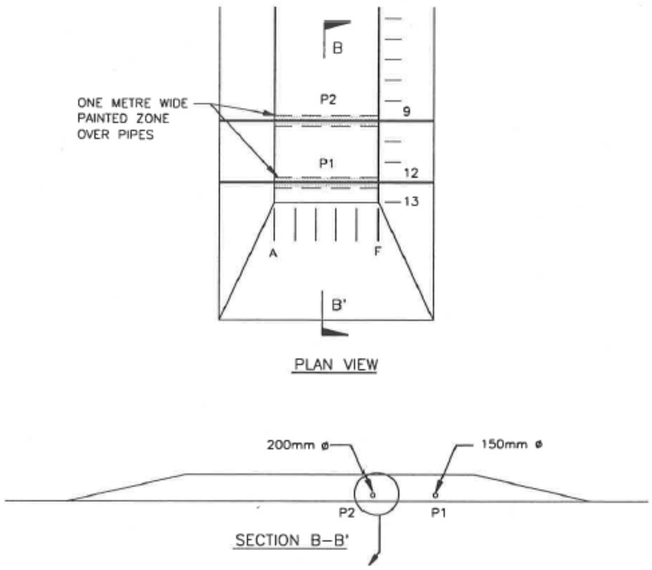
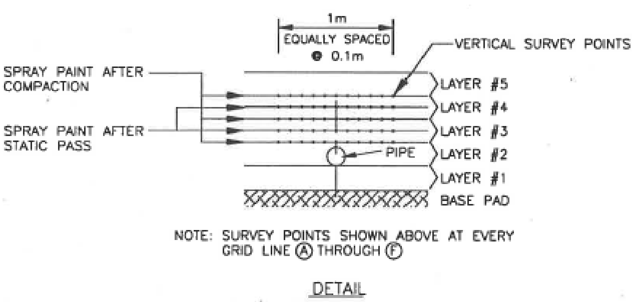


Fig. 2. Plan view and section of test embankments

After the first layer had been placed and compacted, two smooth-surface, straight steel pipes were installed transverse to the longitudinal axis in each embankment, as shown in Figure 3(a). A 200-mm-diameter pipe was installed along gridline 9, and a 150-mm-diameter pipe was installed along gridline 12. After the pipe haunches had been carefully backfilled and compacted, layer 2 was placed and compacted. A 1-m-wide strip, centered on each pipe axis, was then spray-painted on the layer surface and surveyed at closely spaced points, as shown in Figure 3(b). Strips were also spray-painted and surveyed at the top of layers 3 and 4 (after compaction), and at the mid-height of those layers [Figure 3(b)], by placing the layers in half-lifts and smoothing the surface with one static pass of the 6-ton smooth drum roller.



(a) Pipe layout



(b) Monitoring survey grid

Fig. 3. Layout of steel pipes within test embankments

Once fully laid down and spread, layers 2 and 3 of each embankment were compacted with four dynamic passes of the 6- and 10-ton rollers. Layers 4 and 5 were compacted with two passes. Slight subsidence occurred on the north edge of the transition embankment as layers 4 and 5 were compacted with the 10-ton roller. This was compensated by increasing the thickness of the layer by up to 50 mm towards the embankment edge.

FIELD AND LABORATORY TESTS

Field testing of the embankments included density tests, pipe pullout tests, and trench collapse tests. The latter two types of tests were performed upon completion of the embankments to assess the propensity of the materials to support open cracks and cavities in the field. Laboratory testing included gradation tests on the samples retained from the field density pits, and 'sand castle' tests (ICOLD, 1994) on samples of the filter embankment materials.

Field Density Tests

Sixteen field density tests were performed in each embankment during construction. Four tests were performed following compaction of each of layers 2, 3, 4, and 5, two on each compaction lane (approximately at locations 5B, 5E, 10B and 10E in Figure 2). After construction, and excavation to the required depths, six additional tests were performed in the filter embankment, one test in each compaction lane of layers 2, 3, and 4, and four tests in the transition embankment, one in each compaction lane of layers 2 and 4. Table 3 summarizes the average values of dry density measured in the embankments during construction for each roller and number of passes.

Table 3. Average dry densities measured during construction[1]

Embankment	Layer Nos.	No. of Passes	Average Dry Density in kg/m^3	
			6-Ton[2]	10-Ton
Filter	2 – 3	4	1510	1490
	4 – 5	2	1470	1480
Transition	2 – 3	4	1570	1550
	4 – 5	2	1570	1500

Notes: [1] Average of 4 values obtained in layers with equal numbers of roller passes (2 values per layer);
[2] Nominal roller weight.

Densities in the filter embankment were measured using the sand cone test method (ASTM D1556). Those in the transition embankment were measured using the water replacement test method (ASTM D5030). In addition, four measurements were obtained using a nuclear gage in layer 3 of the filter embankment (in close proximity to the sand cone tests). Two nuclear-gage tests were made in layer 2 of the transition embankment. The dry densities measured with the nuclear gage in the filter embankment were within about 1% of those measured with the sand cone. In the transition embankment, the densities measured with the nuclear gage were within about 3% of those measured with the water replacement method.

In the filter embankment, the dry densities measured in the lane compacted with the 6-ton roller were similar to those measured in the lane compacted by the 10-ton roller, suggesting that roller size had a small effect on the resulting density of the materials. The dry densities obtained in the layers compacted by 4 passes of the rollers were slightly higher than those measured in the layers that received 2 passes. Similar trends are seen in the data obtained from the transition embankment. Those data, however, are subject to question due to difficulties experienced with the measurements.

The dry densities obtained in the filter embankment amount to relative densities ranging between about 35% and 45%, which are lower than would be typically expected under similar conditions of lift thickness, compaction equipment, and number of passes. The measured water contents in the filter embankment ranged between about 7% and 9%, which are significantly lower than the optimum water content obtained in the laboratory compaction tests. At a water content of 8%, the dry density obtained in the compaction tests was about 1640 kg/m^3, which is significantly lower than the maximum density of 1770 kg/m^3 obtained at the optimum water content of 16%. Thus, it appears that insufficient wetting during compaction was the main reason for the low relative densities obtained in the filter embankment.

Dry densities obtained on the transition embankment are higher than the maximum density obtained in the laboratory relative density tests, and thus, do not seem meaningful. The high field densities appear to have resulted from difficulties in measuring the volume of the sampled materials, due to inadequate procedures and possibly disturbance during sample excavation and retrieval. Water contents measured on the transition fill ranged between about 4% and 5%.

Field densities measured after construction of the test embankments were in the same range as those measured during construction. Thus, no additional compaction of the materials appears to have occurred under the placement and construction of overlying layers.

Gradation Tests

Gradation tests were performed on the filter and transition materials in the stockpile, after placement in the fill but before compaction, and after compaction in the fill. Three tests were performed on samples from each material stockpile, and four tests were performed on samples from various layers in each fill before compaction. A gradation test was also performed on each sample from the field density tests (16 samples from the filter embankment and 16 samples from the transition embankment). In addition, 2 tests were performed on fill samples of each the filter and transition materials after compaction in the laboratory.

Figure 4 compares the average gradation of the materials in the stockpile with that of the materials in the fill before compaction. This comparison shows that handling and placement of the filter material in the fill (without compaction) increased the percent finer than the 0.15-mm size (No. 100 sieve) from 5% to 7%, due to particle breakdown. Similarly, handling and placement of the transition material increased the percent finer than the 2.36-mm size (No. 8 sieve) by about 2%, as well.

Little particle breakdown occurred during field compaction of the filter and transition materials, once they had been placed and spread in the fills. The average gradations of the materials measured after compaction were very close to those measured before compaction. Throughout the particle size range, the percent finer after compaction of the filter material, regardless of the number of passes or vibratory roller, was within 1% or less of that before compaction. Likewise, the gradation of the transition material after compaction was within 2% of that prior to compaction.

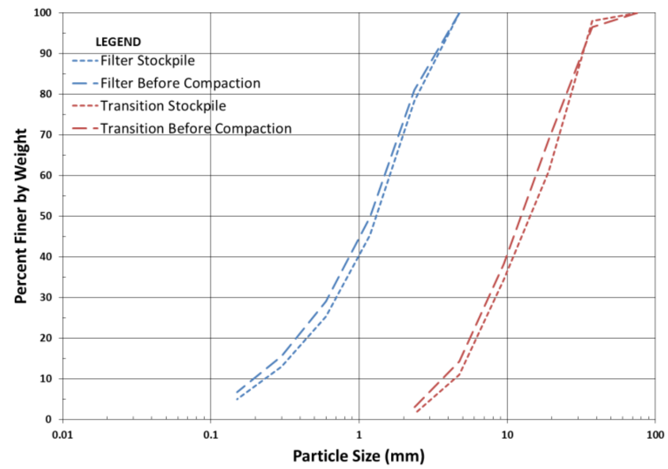


Fig. 4. Average gradations in the stockpile and in the fill before compaction

Laboratory compaction to the ASTM D1557 standard, however, led to significant particle breakdown. For example, the percentage of filter material finer than the 0.15-mm size increased from7% to 9% due to compaction, and the percentage of transition material finer than the 2.36-mm size increased from 3% to 15%.

Pipe Pullout Tests

These tests were devised to examine the propensity of the filter and transition materials to sustain cavities and open cracks that might be created by fault rupture in the dam foundation. The tests consisted of pulling out in a controlled manner the smooth steel pipes that had been previously installed within layer 2 during construction of the test embankments, and observing the collapse of the materials and closure of the pipe cavity, or lack thereof, as each pipe was pulled out.

Prior to each pipe pullout test, a borehole camera was installed inside one end of the pipe. A cable was attached to the other end and was connected to a winch mounted at the rear of a bulldozer, which was positioned along the axis of the pipe at a distance slightly greater than the pipe length away from the embankment. A cushion of transition material was placed halfway between the embankment and the bulldozer to support the pipe and prevent it from sagging as it was withdrawn from the embankment.

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Each pipe was smoothly winched at a rate of approximately 7 cm/sec until it was clear out of the embankment. The embankment sides at the pipe location were then carefully excavated with a steep face, advancing along the pipe alignment towards the center of the embankment. The grid previously laid out on the painted strips was re-surveyed on the advancing excavation face.

Transition Embankment. The 200-mm-diameter pipe in the transition embankment was first to be pulled out. On the side slope of the embankment and in the camera video, the material was observed to collapse immediately as the pipe was withdrawn. Greater collapse of the shoulder was noted at the pipe exit point from the embankment. However, no deformation was observed on the top surface of the embankment.

Upon excavation, no deformation appeared to have occurred on the paint strip at the top of layer 4. Minor deformation was found at gridline F (Figure 2) in the next two paint strips down, which appeared to be related to a small cavity discovered at gridline E at the top of layer 3. The cavity was approximately 1-m long and 100 mm in diameter. It was located directly above the pipe axis, and appeared to rise slightly as it approached the embankment shoulder. The paint strips at the top of layer 2 and middle of layer 3 deformed as shown in Figure 5, fully closing the original pipe cavity.

Collapse of the transition material during pullout of the 150-mm-diameter pipe, was almost identical to that in the first test, except that no cavity was encountered anywhere afterwards, and the original pipe cavity was fully closed. No deformation was observed on the top surface of the embankment or the upper three paint strips, but those at the top of layer 2 and middle of layer 3 deformed as shown in Figure 5.

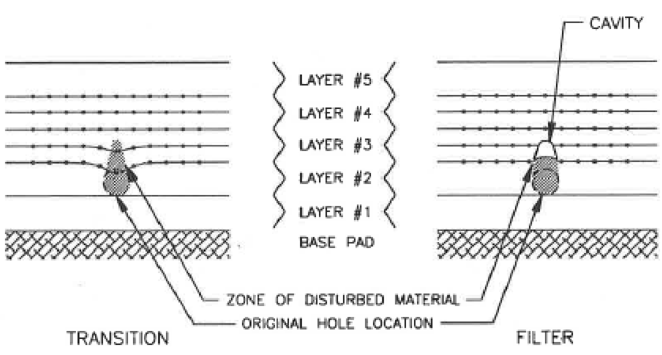

Fig. 5. Deformation and material collapse pattern after pipe pullout tests

Filter Embankment. Only minor material collapse was observed during pullout of the 200-mm pipe from the filter embankment. The video footage indicated that the original pipe cavity remained open along about 90% of the test grid width, and material collapse was greatest at the pipe exit point. After exposing its ends, the cavity remained open for at least 12 hours before water was slowly introduced through a perforated hose laid along the length of the hole. After 2 hours of water flow and negligible collapse, the hose was withdrawn and water was pumped in at a rate of 200 liters/min to flood the cavity. This caused the crown of the original cavity to collapse along its entire length.

Excavation of the embankment revealed no deformation of the painted strips beyond the zone of the cavity collapse. Instead, a new arch-shaped cavity of similar cross-sectional area to the pipe was found in layer 3 above the original pipe location, as shown in Figure 5. On the embankment sides, the new cavity propagated outwards to form chimneys through the shoulders.

Minor collapse was also observed during withdrawal of the 150-mm pipe. The video footage indicated that the pipe cavity remained open along 95% of the embankment width, with collapse at the exit points on the embankment shoulders. The pipe cavity was flooded and underwent similar collapse of the crown as the 200-mm pipe cavity.

Trench Collapse Tests

Two trenching tests were performed in each embankment, approximately along gridlines 2 and 6 (Figure 2), to assess the ability of the filter and transition materials to support open cracks. The trenches were excavated sequentially in layers with a 3.6-ton, rubber-tracked excavator using a 0.5-m-wide bucket. Excavation proceeded until the trench sides collapsed or the base of the embankment was reached.

Transition Embankment. The trench along gridline 2 was excavated first. It collapsed as it was excavated, before a depth of 300 mm was reached. An attempt was made to deepen the trench, but it would not stay open, collapsing as excavation continued. The trench along gridline 6 behaved in a similar manner, and collapsed as it was excavated, before it would reach a depth of 300 mm.

Filter Embankment. One layer at a time, the trench along gridline 6 was excavated the full depth of the filter embankment, until the base pad material was exposed at the bottom. As shown if Figure 6, the trench walls stood vertical, without significant collapse, for approximately one-half hour. Water was then introduced at the trench floor at a rate of 200 liters/min, resulting in minor sloughing of the walls. Once the water reached the top of layer 2, seepage into the embankment balanced the inflow rate, preventing further rise of the water level in the trench.

Fig. 6. Trench walls in filter embankment after excavation

Fig. 7. Trench wall collapse in filter embankment after flooding

The inflow rate was then increased to 600 liters/min and the trench filled in minutes to within 100 mm of the top. Care was taken to minimize wave erosion damage of the trench walls during filling. Once the trench was full, 100-mm-thick wedges of material began sloughing off the trench walls. Several small and one or two large wedges collapsed during the first few minutes. The collapse rate reduced with time as the trench approached a more stable configuration and the water level dropped from outward seepage.

As material collapsed, the fines in the materials dispersed and increased the water turbidity, preventing observation of the failure mechanism in the submerged trench walls. In two hours, the trench had widened to about 1 m at the surface and the water level dropped to a depth of 0.6 m. Inspection several hours later revealed that the trench had collapsed and was filled to about half height along its entire length. The remaining pit was up to 1.3 m wide and less than 1 m deep, with near vertical walls, as shown in Figure 7. A thin layer of fines coated the base of the trench and the lower portion of the pit walls.

Excavation of the second trench also reached the full height of the embankment without collapse. The trench was flooded immediately after excavation, at a rate of 600 liters/min. A slow, controlled collapse mechanism was observed, with small wedges of material sloughing off the sides at increasing intervals. The final configuration of the pit after material collapse was similar to that of the first trench (see Figure 7).

<u>'Sand Castle' Tests</u>

Ten 'sand castle' tests were performed in the laboratory on samples of the filter material from the test embankment, to examine the material's tendency to collapse upon saturation. In addition, two tests were performed on samples processed in the laboratory to have less than 1% of material passing the No. 100 sieve. For all tests, the samples were compacted to 75% relative density at a water content of 8%. The test procedure was as outlined by ICOLD (1994).

The test consists of forming a cylindrical sample of moist material in a 150-mm-high, 100-mm-diameter, Teflon-coated mold. The sample is compacted in 5 layers to selected conditions of density and water content. The mold is then carefully removed by breaking it open, and the compacted sample is left to stand in a shallow tray. If the sample fails to collapse within a few minutes of removal of the mold, the tray is carefully flooded with water and the sample behavior is recorded with time as the water level rises in the tray. To examine the possible development of cohesive bonds with time, the sample may be stored in the mold for varying periods prior to testing.

Four samples were tested using the standard procedure. After removal from the mold, they stood freely for a few minutes with no sign of collapse. As the tray was filled with water, slivers of filter material on the sample perimeter at and below the water level slipped into the tray, undermining the base of the sample. Once the water reached a depth of about 55 mm, about 4 minutes after the start of flooding the tray, the extent of undermining caused the sample to topple into the tray.

Two tests were performed on saturated samples by varying the standard procedure as follows. Once the samples were compacted in their molds, they were slowly saturated until completely submerged. Approximately 24 hours after, the molds were carefully removed from the samples under water. Both samples collapsed immediately to a shallow angle of repose as the confining mold was removed.

To examine the effect of aging and possible cementation of the filter material, four samples were prepared using the standard procedure and allowed to age in their molds for one month under controlled environment conditions. Two samples were tested submerged, after slow saturation, and collapsed immediately upon removal of the mold. The other two samples were tested using the standard procedure and stood freely until the tray was flooded. The collapse mechanism appeared to be the same as that of other samples, although perhaps more rapid. Thus, the tests detected no cementation of the filter material over the aging period examined.

To assess the effects of fines on the tendency for collapse of the material, two samples, processed to have less than 1% material finer than the No. 100 sieve, were prepared and tested using the standard procedure. Like the embankment samples, the manufactured samples stood freely in the dry and exhibited similar collapse characteristics upon flooding of the tray. Comparison of the tests on the manufactured samples with those on embankment samples suggests that a minor amount of fines in the filter material does not have a significant effect on the tendency for collapse of the material when in a moist state.

As a point of comparison, two 'sand castle' tests were also performed on samples of the dam's existing filter zone (referred to as the inner transition), which is known to have cracked under differential embankment settlement and to have allowed piping of the dam core (Sherard, 1973; Gillon, 1988). The test specimens were compacted to the density and water content conditions of the materials in the dam. In contrast to the crushed ignimbrite filter material, the dam's inner transition material showed significant resistance to collapse in the 'sand castle' tests. The samples stood in the flooded tray for periods about 10 times longer than the crushed ignimbrite samples, and even after toppling, the materials remained reasonably intact in water for a significant period.

DISCUSSION

Whereas the pipe pullout and trenching tests indicate that the transition material is cohesionless and will not support open cracks, the tests indicate that the filter material exhibits apparent cohesion in a moist state, and will support cavities and open cracks to depths of at least 1.5 m over substantial periods. Upon saturation, however, the filter material loses its apparent cohesion and collapses immediately, closing open cracks or cavities.

In a moist state, apparent cohesion in the filter material results from the inter-granular stresses induced by capillary forces. In a saturated state, such forces do not exist and the material does not exhibit apparent cohesion, thus collapsing before cavities or cracks can develop. In the case of saturation by a seepage front advancing through previously unsaturated material, capillary action ceases as saturation occurs and the material becomes unable to support cavities or open cracks.

On the above basis, it may be inferred that the filter material below the phreatic surface in the dam will exhibit cohesionless behavior and not support open cracks or large cavities. However, filter materials above the water table are likely to support open cracks and cavities to depths of at least a few meters, which might inhibit the function of the filter.

Such condition is a concern in a case where the dam filter is unsaturated at an elevation below the reservoir level, and sudden cracking of the embankment or core might provide a path for leakage to reach the unsaturated filter. If cracked, the field tests suggest that water flow would quickly saturate the filter materials causing them to collapse and close the cracks. The extent to which this mechanism is successful in closing cracks is likely to depend on the crack size and depth, the flow velocity, and the downstream presence of transition or drain materials that prevent erosion of the filter materials, before the cracks are closed.

If embankment deformations result in small cracks, through which flow velocities are low, it is likely that the filter material would collapse before significant internal erosion takes place. However, in the presence of large cracks or cavities without a downstream cohesionless transition zone, progressive collapse of the filter material may not staunch flows before significant erosion occurs. Thus, in a situation where large cracks or cavities may develop suddenly in a dam, zones of cohesionless transition materials are necessary to prevent erosion of filter materials that may crack temporarily and are situated below the reservoir level.

As demonstrated by the 'sand castle' tests, the density of the filter materials is likely to have a relatively small effect on their tendency to collapse upon saturation. Accordingly, it is important to compact the materials to such density that they will have adequate strength. However, excessive compaction that may cause substantial particle breakdown is not desirable.

In the case of the Matahina dam, the retrofit design consisted of a thick filter, flanked by thick zones of transition and drain materials, and a downstream rockfill. Such arrangement represents a very safe design capable of withstanding cracking and cavities that might result from large fault rupture displacements in the dam foundation (Mejia et al, 1999).

SUMMARY OF CONCLUSIONS

A field and laboratory test program was performed to evaluate the suitability of a crushed ignimbrite rock for use as filter and drain material for the seismic retrofit of the Matahina Dam in New Zealand. The program included construction of two test embankments and field tests of the materials' tendency to exhibit 'apparent cohesion' and to support open cracks. Laboratory tests were performed to supplement the field tests.

The test program showed that the ignimbrite rock can be processed to manufacture filter and transition materials with adequate gradation and durability characteristics, and acceptable particle shape. The VSI crusher was effective at producing equidimensional particles from a rock that, because of its mineralogy and lenticular nature (as an agglomeration of glassy shards), otherwise exhibits a tendency to break in highly elongated particles.

Medium to low relative densities were obtained in the filter embankment, apparently as a result of inadequate wetting of the material during compaction, and perhaps an insufficient number of roller passes. Nonetheless, laboratory testing of the filter materials showed that if compacted to an adequate relative density, the materials will have satisfactory strength. High field densities were recorded in the transition embankment, apparently due to difficulties in measuring the volume of the sampled materials, because of inadequate procedures and disturbance during sampling.

Breakdown of the filter and transition material during construction of the test embankments was minor. Breakdown (mostly of coarse particles) occurred primarily during handling and placement on the test embankments, resulting in an increase of about 2% in the percent of filter and transition materials passing the No. 100 and No. 8 sieves, respectively. Little particle breakdown occurred during compaction, even under 4 passes of a 10-ton vibratory roller. On the other hand, compaction in the laboratory to the ASTM D1557 standard resulted in significant breakdown. Thus, the maximum density obtained in that test is not representative of the maximum density that may be obtained for the material without particle breakdown.

The pipe pullout and trenching tests indicate that, even in a moist condition, the transition material is cohesionless and is unable to support open cracks or significant cavities. In contrast, the tests indicate that the filter materials exhibit 'apparent cohesion' in a moist state and, in spite of being loose to medium dense, will support moderate size cavities and open cracks to depths of at least 1.5 m over substantial periods. If very loose, it appears the materials will collapse and are unable to support open cracks under typical field moisture conditions. In a saturated state, or upon saturation, the filter materials are cohesionless and collapse immediately precluding the opening of cracks. The 'sand castle' tests indicated that no strong cementation bonds formed in the compacted filter material over a period of one month. The tests also indicated that, for fines contents less than about 5%, the materials' tendency for collapse upon saturation does not appear to be affected significantly by small variations in the fines content.

In summary, the test program confirmed that suitable filter and transition materials may be obtained by crushing and processing the ignimbrite rock available near the Matahina Dam site. Although the filter material displays apparent cohesion and will support cracks in a moist state, it collapses immediately upon saturation. Based on the test program, it may be concluded that, flanked by a zone of cohesionless transition material, the crushed ignimbrite yields a satisfactory filter for the seismic retrofit of Matahina Dam.

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REFERENCES

International Commission on Large Dams (ICOLD), [1994]. *"Embankment Dams Granular Filters and Drains,"* ICOLD Bulletin No. 95, Paris.

Gillon, M. [1988]. *"The Observed Seismic Behavior of the Matahina Dam"*, Proceedings, Second International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri.

Mejia, L., Forrest, M., Bischoff, J., Gillon, M., and Everitt, S., [1999]. *"Upgrading of Matahina Dam for Foundation Fault Displacement,"* Proceedings of WaterPower '99, ASCE, Las Vegas, Nevada.

Sherard, J.L. [1973]. *"Embankment Dam Cracking",* in *Embankment-Dam Engineering*, (R.C. Hirschfeld and S.J. Poulos, ed.) John Wiley and Sons, pp. 271-353.

Woodward-Clyde Consultants, [1996]. *"Matahina Dam Strengthening Project, Phase III, Ignimbrite Trial Embankment Construction and Testing,"* Report prepared for Electricity Corporation of New Zealand.