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Effects of tsunami on coastal ground conditions and appropriate measures for rail track rehabilitation

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Mohammad Hadi Khabbaz
University of Wollongong, khabbaz@uow.edu.au

A. Puswewala
University of Moratuwa

W. Bandara
Engineering Laboratory Services Ltd.

EFFECTS OF TSUNAMI ON COASTAL GROUND CONDITIONS AND APPROPRIATE MEASURES FOR RAIL TRACK REHABILITATION

B. Indraratna and H. Khabbaz
School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW, 2522, Australia

A. Puswewala
Senior Lecturer, University of Moratuwa, Sri Lanka

W.A.A.W. Bandara
Managing Director, Engineering Laboratory Services Ltd., Colombo, Sri Lanka

ABSTRACT

On boxing day, 26 December 2004, the largest earthquake for more than 4 decades, (magnitude 9.0) occurred between the Australian and Eurasian plates in the Indian Ocean (along the overly stressed Sunda trench) to the west of Aceh Province (Northern Sumatra). The quake triggered a series of waves that increased in height rapidly close to the shore (tsunami) spreading thousands of kilometers across the Bay of Bengal. In the Eastern and Southern coastal belt of Sri Lanka, the floodwaters reached almost 1 km inland, causing extensive damage to infrastructure and fatalities of unprecedented proportions. Widespread destruction included several kilometres of rail tracks, dislocating the track elements from the remoulded surface soil. Near the beach town of Hikkaduwa, the ferocity of the waves was evident with the total destruction of tracks within 150 m from the shore, and overturning a crowded intercity train (over 1000 fatalities). In this paper, the relevant aspects imperative for the robust reconstruction of dwelling and rail tracks on such devastated ground are elucidated, based on the field observations and soil tests conducted several weeks later at the site of the train disaster. Visual examination and CPT tests indicated that the sandy topsoil was turbulently blended with transported marine sediments including organic fines. Under excessive hydraulic gradients, the geotechnical properties of surface soils up to a meter or more have been significantly altered. At some locations near the surface, the void ratios have almost doubled once the waves receded and the soil re-deposited. Revised ballast grading and enhanced track conditions are considered, including the essential need for the formation soil stabilization. The use of geocomposites (i.e. bonded geogrid-geotextile layers) and associated benefits are described, with the aim of achieving reduced track settlement, increased resilient modulus and decreased ballast degradation. The benefits of increasing the confining pressure on track are also highlighted in relation to particle breakage.

INTRODUCTION

A tsunami travels from source area (usually earthquake epicenters) as a series of concentric waves. In the deep sea, these waves can travel at speeds of 500 to 800 km/h from the epicenter, but approaching the shore, the waves decrease in speed to 20-30km/h while increasing the height as the kinetic energy transforms to potential energy. A wave that is only a meter in height in the deep ocean can grow to a few tens of meters at the shoreline (ITIC, 2000). Destruction caused by tsunamis is the direct result of three factors: impact, inundation, and erosion. Both the incoming and receding waves can lead significant erosion of coastal sandy soils as well as inducing piping under excessive hydraulic gradients, undermining bridge piers, loss of foundation bearing capacity and confinement, apart from the obvious damage to structures upon wave impact.

The Boxing Day tsunami in December 2004 devastated several South and Southeast Asian countries including Indonesia (Northern Sumatra), Thailand (Phuket), Sri Lanka (Eastern and Southern Provinces), South India, Andaman and Maldives islands. The epicenter of this earthquake was measured as 9 on the Richter scale. As a consequence of the vertical 'throw' of the large discontinuity plane thus formed, high velocity ripples (more than 700km/h) thus formed transformed to tsunami as the shallow depths (shorelines) were approached. While in most countries, the tidal waves directly impacted on the coastal belt, in Sri Lanka, while the eastern coast was destroyed by direct wave impact, its southern coast (Fig. 1) was also severely damaged by the turbulent and rebound waves with considerable angular momentum with heights still reaching over 10m. The damage caused by these turbulent waves were so catastrophic that hardly any houses and other buildings within a100m proximity to the shore were spared in many places, and even the well built rail tracks and highways that have lasted for many decades were totally destroyed. The coastal stretch near the famous tourist beach town of Hikkaduwa was so badly hit that over 1000 passengers lost their lives and many others injured, when the tsunami hit a crowded intercity train, derailing, toppling and submerging its carriages, making this train disaster the worst rail accident ever to be recorded. The probable lifting and piping of the formation soil beneath the track caused demounting of the track, lifting it up with the tidal waters and displacing it several meters.

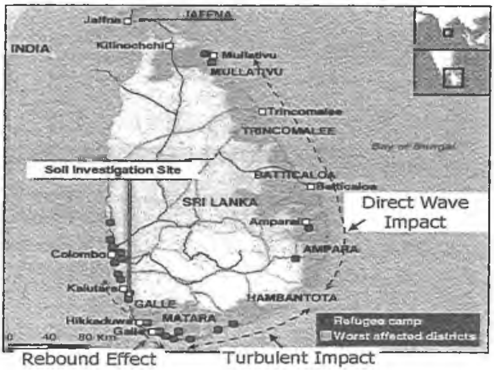

Fig. 1 Tsunami Impact on Sri Lanka (Map is Courtesy of www.news.bbc.co.uk, Jan. 2005)

Site reconnaissance of the site of this train disaster was conducted under the guidance of the first author with the assistance provided by University of Moratuwa and Engineering Laboratory Services Ltd. The field observations indicated areas of significantly disturbed surface soils (at some locations up to 1 m), now a heterogeneously mixed medium composed of the original topsoil blended with very fine beach sands, silts and organic sediments transported by the waves and construction materials (debris) turbulently mixed *in situ*. A sketch of this turbulent mixing is shown in Fig. 2 for a typical coastal area affected by tsunami waters. Once the waves receded, the 'piping' sands, eroded top soils, transported fine sediments (including organics) and debris have settled at a much higher porosity compared to the originally compacted sandy soil that have existed for hundreds of years (Fig. 3).

Sri Lanka has experienced a number of tsunamis given the past historical periods dating back over 2000 years, the last tsunami reported in June 1941 as result of the earthquake of Magnitude 8.1 near Andaman islands (Wattegama, 2005). This paper will elucidate the need for rebuilding rail tracks that are more resistant to future tsunamis as well as more resistant to possible earthquake tremors that Sri Lanka is now prone to. Given the recent history of earthquake epicenters and plate tectonics in the vicinity of the Sunda trench, Sri Lanka cannot be ruled out as earthquake free any longer. Especially where the coastal fine sands are prone to liquefaction, the roads and rail tracks require much more robust design implementation. The use of geotextiles to accelerate the dissipation of cyclic pore pressures, the use of geogrids to stabilize the ballast bed, and the increased confining pressure on tracks to minimize lateral strains are some of these aspects that are imperative to consider through sound research evidence.

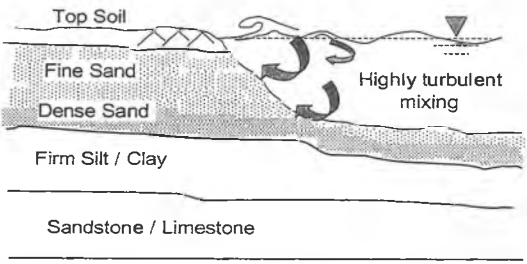

Fig. 2 Typical Layers of Coastal Soils due to Million Years of Geological Deposition

PRELIMINARY SITE INVESTIGATIONS

A trial pit dug at an affected site indicated blended surface sands with no distinct layering, and clean relatively undisturbed sand was found at a depth exceeding 450 mm (Fig. 4). The particle size distributions (Fig. 5) indicated a more obvious well-graded nature of the sand closer to the surface, in the areas where the beach sand was well known to be very uniform before the tsunami. The uniformity coefficient has changed form 1.6 to 4.6 in this particular location as a result of mixing. A standard cone penetrometer test (CPT) and A cone penetrometer test with pore pressure measurement (CPTU) were conducted to re-examine the soil profile up to 10m deep (Fig. 6), on the site of the train disaster. The totally wrecked train is now erected on the abandoned part of track as seen in the background. Figures 7 and 8 illustrate measured parameters obtained from CPT and CPTU, respectively. The friction ratios determined for the shallow depths (less than 1 m) indicate metastable sands and/or mixed soils with increased sensitivity. It is also shown that soil layer up to 1m was completely remolded by flooding. The surface compaction is essentially required to improve the ground condition. At greater depths exceeding 2 m, the stable cohesionless sand deposits (unaffected by the tsunami) could be established from the CPT and CPTU profiles (Figs. 7 and 8). The piezocone tests also indicated the increased pore pressures at various depths due to the presence of organic (peat) seams and clayey sand/silt deposits that now carry increased moisture content due to the infiltration of water through the relatively pervious top sand layers (Fig. 8). The hydrostatic pore pressure increases linearly and starts at the ground surface. The presence of peat layer is clearly identified by the suddenly increased friction ratio.

Fig. 3 The Surface Soil has been a Blended with Sand and Soft Transported Sediments and Crushed Debris (near the City of Galle, Sri Lanka)

Fig. 4 Mixed Sands with Fine Organic Sediments at Shallow Depths Followed by Undisturbed Coarser Sand at Greater Depths

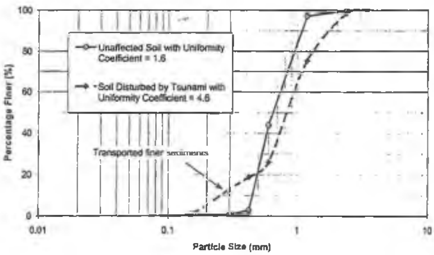

Fig. 5 Particle Size Distribution Curves of the Tsunami Affected and Unaffected Soils

Fig. 6 Using A Cone Penetrometer Test to Re-Classify the Soil Profile at the Site of the Catastrophic Train Derailment

The soil properties of 2 soil samples in tsunami-affected area are given in Table 1. The void ratio of sample 1 at 600 mm depth is about 0.7, which is much higher than the initial pre-tsunami void ratio estimated to be less than 0.5 on the compacted surface. Assuming this range of void ratio and an associated saturated unit weight of about 21 kN/m^3, the critical hydraulic gradient, i_{cr}, can be estimated from:

$$i_{cr} = (\gamma_s / \gamma_w) - 1 \approx 1.14 \tag{1}$$

where γ_s= unit weight of saturated soil and γ_w = unit weight of water. The above value of i_{cr} implies that a rapid flood with a flood height greater than 1 m may induce piping of the shallow surface soils to a substantial depth.

FORMATION MODIFICATION

In many tsunami-affected areas in Southern Sri Lanka, the total rail track structure has to be removed before carrying out any reconstruction. Therefore, the subgrade condition should be carefully examined and appropriate measures have to be taken to improve the formation soil performance. One of the most important steps at the preliminary stage was identifying and classifying the subgrade soils. Although limited subsurface exploration has been conducted in the site, no rail rehabilitation mission will be completed without reanalyzing the post-tsunami soils strength and densities along the coastal rail track and comparing this data with the pre-tsunami soil profiles and data, past geological maps and geotechnical reports. In general, two types of subgrades: (a) loose fine sand and (b) soft silty or clayey sediments need special consideration, as they are highly susceptible to failure under cyclic train loading, including excessive plastic deformation and piping. Some differential settlement would be inevitable in some parts of the track that required urgent reconstruction for passenger transport without appropriate soil improvement (Fig. 9) but of course at a reduced train speed. For stabilizing the formation soils, a variety of options of ground improvement are available in Sri Lanka. For these techniques, monitoring during and after construction with the aid of proper instrumentation is highly recommended. Some selected key means of subgrade enhancement are discussed in this section.

Table 1 Soil Properties

Number	Depth (h)	Water Content (w%)	Dry Density (ρ_d)	Void Ratio (e)	Degree of Saturation (S_r)
Sample 1	600 mm	12%	1593 kg/m^3	0.68	47.3%
Sample 2	1000 mm	17%	1690 kg/m^3	0.59	77.2%

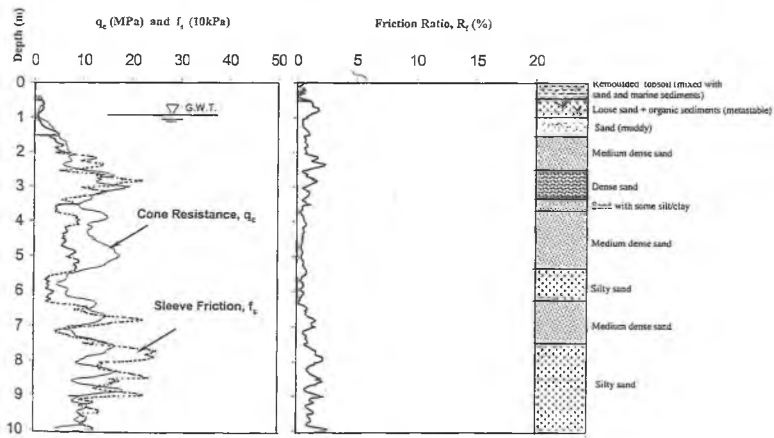

Fig. 7 Cone Penetration Test Results of Soil Layers (CPT) after Tsunami Occurrence (Site 1)

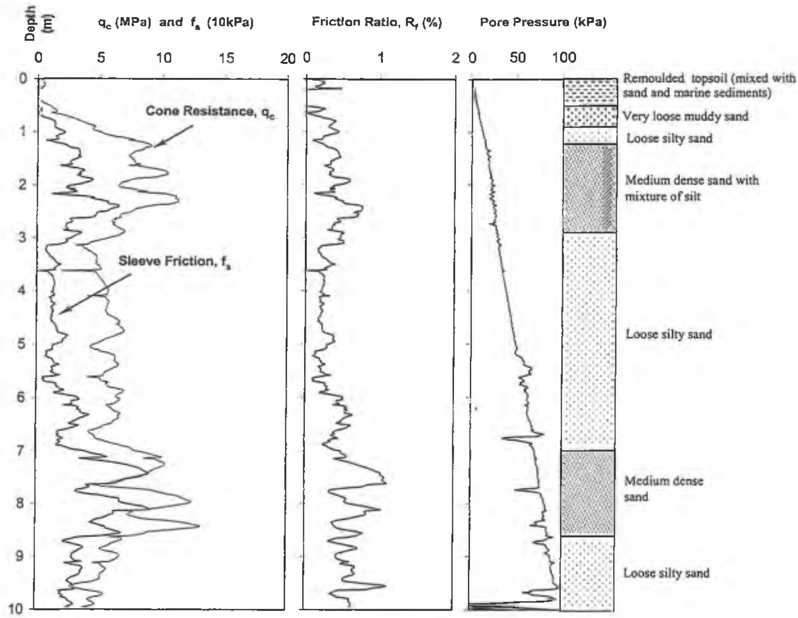

Fig. 8 Cone Penetration Test with Pore Pressure Measurement Results (CPTU) of Soil Layers after Tsunami Occurrence (site 2)

Fig. 9 Passenger Rail Track Reconstructed after Tsunamis Occurrence without Appropriate Subgrade Improvement (near the City of Galle, Sri Lanka)

Loose Sand Subgrade

The preliminary site reconnaissance indicated that the disturbed top layer of the soil includes mixed soils such as loose sand with marine sediments (including dark brown to black organics). Densification of loose granular soils, heterogeneous soils and liquefiable soils can be achieved by surface compaction. The purpose of densification is to increase the relative density and the internal friction angle of the soil, thereby reducing the post-construction settlement as well as increasing the bearing capacity.

The surface compaction is highly regarded as the simplest and the cheapest method for densification of loose, saturated and cohesionless remolded soils in the Tsunami affected areas. This method reduces the void volume of remolded soil by forcing the soil particles into the tighter state using either static or dynamic forces. In the field, the soil up to 1m deep can be compacted using rolling and kneading, vibrating and ramming. The performance of field compaction depends on soil dry density, moisture content, amount of compaction and soil type (Bergado et al., 1994).

Due to various factors affecting the densification process to achieve the desired results, field monitoring and quality control tests must be conducted during and after the vibro/dynamic compaction program. Generally, site investigation and verification can include: standard penetration test (SPT), cone penetration test (CPT) and plate load tests, which are available in Sri Lanka through various private geotechnical agencies, such as ELS Ltd.

Compaction is the most cost effective technique for enhancing the bearing capacity and stiffness of loose sand. However, grouting technology or chemical stabilisation can also be used as alternatives to retard water seepage and to increase the shear strength of loose sand formations. For preventing formation collapse during large earthquakes, deep mixing method may be employed to increase the liquefaction resistance of the loose sand beneath rail track and improve its stability. Although a variety of chemical additives has been developed and used for admixture stabilisation, most frequently used additives nowadays are lime and cement due to their affordability. A comprehensive overview of the ground improvement techniques for loose sand can be found in Terashi and Juran (2000). In Sri Lanka, the possible use of lime/cement piles underneath rail tracks has been discussed but not yet implemented.

Clay Subgrade

In the region of the trial site of soil exploration, no deep layers of soft clays were found up to depths approaching 15 m, but clayey sands and organics layers encountered will still show some compressibility. However, many coastal regions of Southeast Asia contain soft clays (estuarine or marine), which have poor geotechnical properties such as low bearing capacity and high compressibility. In the City of Colombo itself and to the south of Colombo towards the Southern Province that was devastated by the tsunami, compressible clays and peaty soils are often encountered, and some of these areas only just escaped the wrath of the tsunami. If these areas had been flooded, the subsequent settlement of buildings may have been substantial. Transport infrastructure including rail tracks are affected by the settlement and lateral movement of soft formation soils, in the absence of appropriate ground improvement prior to track reconstruction. In Sri Lanka, the improvement of clayey soft soils also requires equal attention as much as the loose sandy deposits in the Southern and Eastern provinces. This is because towards the City of Colombo not only the coastal population increases, hence the need for taller buildings, but also the extent and the frequency of soft clays and peaty soils increase. Cost effective techniques for ground improvement are now employed for compressible formation soils in Sri Lanka. Some popular methods include: (1) stabilization by chemical admixtures, (2) geosynthetic reinforcement and (3) preloading and use of prefabricated vertical drains.

1. *Stabilization by Chemical Admixtures*: Chemical modification involves mixing and compaction of near-surface soil to improve consistency, strength, deformation

characteristics and permeability. These improvements become possible by the ion exchange at the surface of clay minerals, bonding of soil particles and filling of void spaces by chemical reaction products. Various types of grouting techniques can also be used in chemical stabilisation. To stabilise deep layers of soft formations, lime-cement columns can be installed. Implementing lime-cement columns with column diameter of 0.5-0.6 m and depth of 5-15m under the rail tacks in a ladder grid can reduce the displacement of the track structure substantially (Kaynia et al., 2005). Nevertheless, the use of chemical admixtures raises environmental concerns particularly in the coastal areas of Sri Lanka, when the groundwater table is very high. Groundwater contamination by injected chemicals is serious and should be considered in the selection of appropriate measures.

2. *Geosynthetics:* Railway subgrades of moderate to poor quality can be improved by the use of geosynthetics. Geosynthetic reinforcement can provide a safe and economical alternative to the conventional practice of deep foundations. This method can also be used in combination with other ground improvement techniques, such as wick drains and lime-cement columns to improve the rate of consolidation. Various aspects of using geosynthetics in reconstruction of rail tracks in tsunami affected regions are explained in Section 5.1.

3. *Preloading and Vertical Drains*: Preloading is the one of the most successful ground improvement techniques that can be used in soft soil subgrades. It involves loading of the ground surface to induce a greater part of the ultimate settlement that the ground is expected to experience after construction. Installation of vertical drains can reduce the preloading period significantly by decreasing the drainage path length (radial direction), as the consolidation time is inversely proportional to the square of the length of the drainage path. Due to the rapid initial consolidation, vertical drains will increase the stiffness and bearing capacity of soft foundation clays. Application of vacuum pressure with surcharge loading can further accelerate consolidation while reducing the required surcharge fill material without any adverse effects on the stability of an embankment built on soft clay. This practice saves time in the absence of a high surcharge embankment.

GUIDELINES FOR HOUSING FOUNDATIONS IN THE TSUNAMI AFFECTED AREAS

Rehabilitation of tsunami victims is of paramount importance in future sustainable development plans in Sri Lanka. In this section, some guidelines for reconstructing low-cost dwellings in the affected coastal areas are proposed, in terms of: (a) locations and alignment of houses and (b) appropriate foundation design.

Locations and Alignment of Houses

1. Dwellings should be constructed at a 'safe distance' of at least 100-200m away from the beach depending on the area (eg. presence or absence of mangroves, sand dunes, etc). The Eastern part of Sri Lanka is more prone to direct waves from the Indian ocean, whereas the Southern part of the island may receive rebound waves.

2. Housing in areas behind densely grown palm trees (coconut and palmyrah) may be encouraged (Fig.10). These palms have fibrous root systems which facilitate the intake of groundwater from soil as deep as 2-3 meters. They provide high suction to hold together large volumes of fine soils that can otherwise be disturbed or remoulded by extreme

hydraulic gradients. Moreover, these strong roots provide excellent natural reinforcement for sandy coastal soils, increasing the apparent bearing capacity considerably.

3. For land at almost sea level, typical dwellings should be constructed on a raised earth platform in the order of 0.6-1m in height, to provide protection against flooding and foundation scouring (Fig.11).

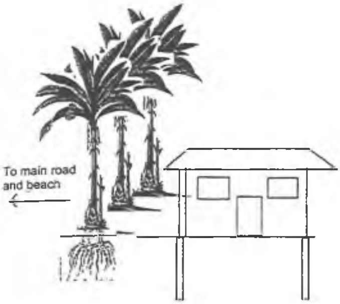

Fig. 10 Protection from Tree Line

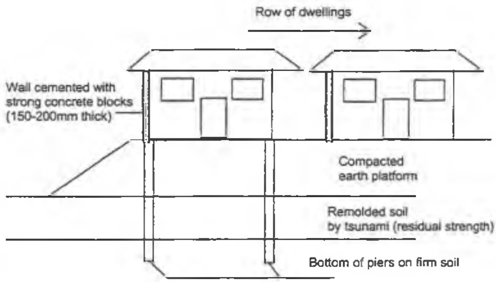

Fig. 11 Housing Construction on Raised Earth Platform

4. Dwellings may be constructed such that the strong masonry side faces the direction of waves (Figure 12). Mangroves must be encouraged as much as possible within the 'safe distance'. A group of houses should be arranged in a parallel pattern rather than random to create channels for the waves to pass through easily, with minimum damage.

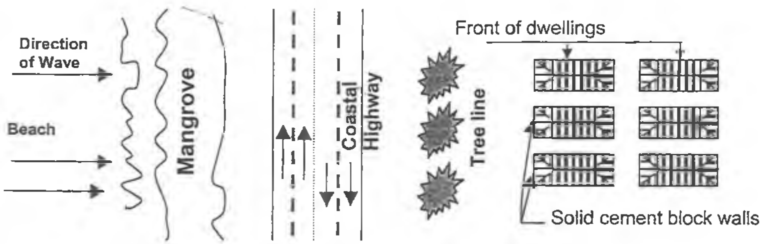

Fig. 12 A Preferable Arrangement for a Group of Houses

Recommended Foundation Design for Housing Units

1) At sites affected by tsunami, proper soil investigations based on Cone Penetration Test and/or Standard Penetration Test should be carried out to determine the degraded soil properties and their distributions. The depth to sound (unaffected) soil layers needs to be estimated and the bearing capacity evaluated on the basis of shear strength.

2) Weakened soil conditions in some areas (1-2m depth) should be stabilized by appropriate ground improvement techniques discussed previously. Removal of transported soft marine sediments up to 200 mm from the soil surface is required, in some areas.

3) In order to provide strong strip footings, at least 250mm wide trenches may be excavated up to 600mm deep and the bottom of these trenches compacted to about 95% relative density. Subsequently, a 200-250mm thick compacted gravel (size 7-10mm) layer may be placed at the bottom of the trench to provide a good drainage medium as well as to increase the bearing capacity (Fig. 13). The gravel layer will rapidly dissipate excess pore pressure and also act as a damping layer in case of earthquake tremors. Concrete piers should be installed about every 3m and at all corners of the dwellings as shown in Figure 14. These piers may be up to 1.5m deep, resting on the medium dense sand, affected by tsunami.

4) Finally, the reinforced concrete footings should be placed above the compacted gravel layer to erect the houses (Figs. 15 and 16).

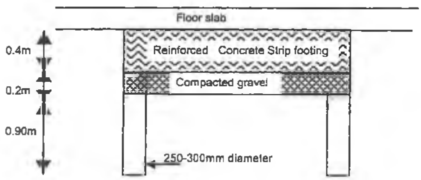

Fig. 13 Foundation for Soils Affected by Tsunami (Section A-A)

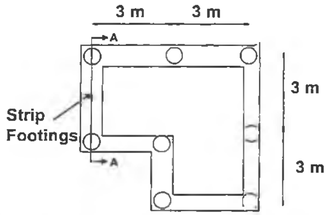

Fig.14 Typical Plan View of Foundation Construction

Fig. 15 Constructions of Walls with Concrete Bricks, during Reconstruction

Fig. 16 A Completed Dwelling According to the Guidelines Stated Earlier, Supervised by the First Author

SUBBALLAST OR FILTRATION LAYER

Subballast is the layer of aggregates placed between the ballast layer and the subgrade. This is usually comprised of well-graded crushed rock or a sand/gravel mixture. The subballast layer should be designed to prevent the penetration of coarse ballast grains into the subgrade, and the upward migration of subgrade fines (formation soil) into the ballast layer. Therefore, subballast acts as a filter and a separating layer in the track substructure, which transmits and distributes stress from the ballast layer down to the subgrade over a wider area. It also acts as a drainage medium to dissipate cyclic pore water pressures developed by the passage of trains. Some properties of subballast are given in Table 2.

Using geotextiles in conjunction with a sand-capping layer is highly recommended for track subballast. The sand filter in this case prevents the migration of fine soil upwards, and the geotextile acts as a separator between the sand and ballast. Raymond (1986) recommended the non-woven needle punched geotextiles in preference to woven geotextiles, because the woven geotextile, unlike the non-woven fabric, is unable to dissipate excess pore pressures quickly enough within the geotextile plane (Raymond 1986). This is particularly important in the case of freight trains that are both very heavy and very long.

Table 2 Some Properties of Subballast Materials

Property	Value	Ref.
Maximum percentage finer than 75 μm	5%	AREMA (2003)
Uniformity Coefficient ($C_u = D_{60} / D_{10}$)	$6 < C_u < 20$	Selig and Waters (1994)
Maximum loss in LAA Test	50	ASTM C131
Maximum liquid limit (LL) of the fraction finer than 425 μm	25%	Selig and Waters (1994)
Maximum plasticity index (PI) of the fraction finer than 425 μm	6	Selig and Waters (1994)

Drainage

Drainage plays a significant role in the stability and safety of a track substructure. Although the grading and compaction of the subgrade is the first defense against water absorption, it is also clear that if adequate rainfall or other sources of water are available, the subgrade can become saturated over time. The ballast begins to push down into the formation resulting in the loss of both longitudinal profile and cross level. It is therefore essential to collect and remove water, which percolates through the ballast and accumulates in the subballast and at the intersection of the subgrade. To construct a satisfactory drainage system, it is essential to examine the groundwater, hydrological and subsurface conditions of the site. To provide a suitable track drainage, the surface of the subballast and subgrade should be sloped towards the sides. In addition, suitable channels (e.g. ditches or conduits) are required to carry away the water coming from the track substructure (Fig. 17).

Geosynthetics in drainage applications have shown a remarkable capability including in rail track drainage system. Thick-needle punched geotextiles and geonets/spunbonded geotextile composite systems exhibit effective drainage (De Berardino, 1992). The use of geonets as part of a drainage system has increased dramatically over the past decade. Geonets, manufactured from chemically resistant polyethylene, are lightweight and flexible rolls that need only to be unrolled, cut and positioned, resulting in considerable time savings. They take up less space, are cost effective and are easier to install than their traditional granular counterpart with similar hydraulic characteristics. Geonets usually have two sets of parallel-extruded polymer strands intersecting at a constant angle (between 60° to 90°). Strands of one set lie on the top of strands of the other set, and the two sets of strands create two sets of channels which can convey water. There are three major design considerations with geonets: (a) flow rate, (b) compressive strength and (c) hydraulic gradient. Geonets can play a role as drainage core wrapped with a non-woven geotextile. This geocomposite drainage system can be used instead of conventional sand or gravel covered pipe drains. The soil particles are held back by the non-woven filter fabric allowing just the water to pass through to the drain core.

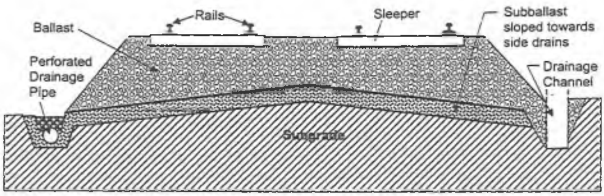

Fig. 17 Schematic Illustration of Track Drainage System (after Selig and Waters, 1994)

BALLAST AND TRACK MODIFICATION

Ballast is the largest component of a track by weight and volume. While ballast is expected to be low-cost and in adequate supply, it also has to be capable of providing the engineering requirements of the rail track. The main functions of ballast are: the distribution of loads received from the sleepers, damping of dynamic loads, providing lateral resistance and providing rapid drainage. Supplying high quality fresh ballast for reconstruction of rail track for entire region affected by tsunami is costly and time consuming. Therefore, the existing ballast of the damaged tracks can be reused, except for some areas that the track substructure has been totally washed out by the waves. Obviously, old ballast should be totally removed, cleaned, sieved and recompacted. Recycling of the in place ballast not only reduces the cost of track rehabilitation, but also contributes to waste reduction and decreases the need for extensive quarrying and environmental degradation. However, research at University of Wollongong (e.g. Indraratna et al., 2002, 2004) has indicated that waste ballast after being loaded for some time is known to suffer from micro-cracks causing reduced resiliency. Recycled ballast has lower internal friction angle due to attrition and reduced angularity, hence exhibiting a higher settlement and lateral deformation compared to those of fresh ballast upon cyclic loading. In order to improve the geotechnical properties of recycled ballast, inclusion of geosynthetics should be taken into account.

Geosynthetics

Geosynthetics have been used in various ways in new rail tracks and track rehabilitation for more than three decades. The purpose of the application of geosynthetics within railway construction, similar to other geotechnical engineering projects, can be divided into six categories: (a) separation, (b) reinforcement, (c) filtration, (d) drainage, (e) moisture barrier or waterproofing, and (f) protection. In new tracks, the geosynthetics are installed directly on the subgrade or subballast layer. In track rehabilitation, if the formation quality is acceptable, geosynthetics are installed on top of the old ballast, which has either been trimmed or embedded in the original subgrade formation (Ashpiz et al., 2002). There are several problems that should be considered in rail track construction, namely, increasing the bearing capacity of subgrade soil, preventing the contamination of ballast with subgrade fines and the dissipation of high pore water pressures built up by cyclic train loading. Geosynthetics can offer an economic solution to theses problems if they are selected an implemented appropriately.

A general study on railway rehabilitation was conducted by Raymond (1999) in North America. He performed several experiments with different geotextiles placed under ballast. Accordingly, he concluded that well-needled nonwoven geotextiles with weight (mass per unit area) more than 500 g/m^2, are environmentally the most stable geotextiles for use in railroad bed rehabilitation. He also found that the greatest application of geosynthetics was in poorly drained regions of the terrain that were flat and possibly marshy. Enhancing the performance of rail tracks by composite geosynthetics is now actively considered by rail industry. As Rowe and Jones (2000) have described, geocomposites can provide reinforcement to the ballast layer, as well as filtration and separation functions simultaneously. The combination of geotextiles and geogrids is considered to maximise the benefits to the railway tracks in the following ways: geogrids can provide tensile reinforcement and shear resistance to increase the effective bearing capacity of the subgrade, and also to interlock with the ballast and increase its resistance to both vertical and lateral movement; whereas nonwoven geotextiles are used for separation and filtration, preventing fouling of ballast and providing quick relief of pore water pressures.

Improvement of Recycled Ballast Using Geosynthetics

The deformation and degradation behaviour of fresh and recycled ballast was investigated in a large triaxial chamber (Figure 18) simulating a small track section. This large-scale prismoidal triaxial rig of 800 mm length, 600 mm width and 600 mm height was designed and installed at the University of Wollongong (Indraratna et al., 1998) to model the cyclic loading response of ballasted tracks. By allowing the lateral strain of ballast upon loading, the triaxial rig with unrestrained sides provides a reliable facility for physical modeling of ballast. The stabilisation aspects of recycled ballast using various types of geosynthetics were also studied in these model tests. The effectiveness of various geosynthetics in stabilising recycled ballast was investigated through laboratory model test results. Three types of geosynthetics were used including woven geotextiles, geogrids and geocomposites. The tests were conducted in both dry and wet conditions to study the effects of saturation. The testing procedures together with complete findings and discussions have been reported by Indraratna et al. (2002). Only selected results illustrating the effects of inclusion of geocomposites (bonded geogrids and non-woven geotextiles) on ballast settlement and breakage are given in this paper.

Fig. 18 Large-Scale Prismoidal Triaxial Equipment Built at the University of Wollongong

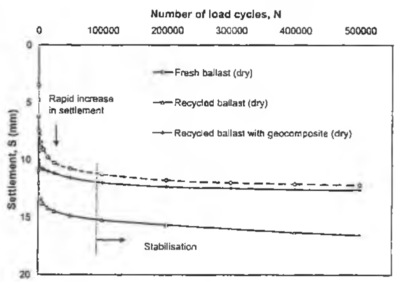

Fig. 19 Settlement of Fresh Ballast and Recycled Ballast with and without Geosynthetics (dry samples)

Figures 19 and 20 show the settlement of fresh ballast without any reinforcement and recycled ballast with and without the inclusion of geosynthetics in dry and wet status, respectively. As expected, dry fresh ballast gives the least settlement. It is believed that the higher angularity of fresh ballast contributes to better particle interlock and therefore, causes less settlement. The test results reveal that wet recycled ballast (without any geosynthetic inclusion) generates significant settlement, because, water acts as a lubricant thereby reducing the frictional resistance and promoting particle slippage. Although geogrids and woven geotextiles decrease the settlement of recycled ballast considerably, the geocomposite (geogrid bonded with non-woven geotextiles) stabilises recycled ballast remarkably well (Indraratna et al., 2003). The combination of reinforcement by the geogrid and the filtration and separation functions provided by the non-woven geotextile component (of the geocomposite) reduces the lateral spreading and fouling of ballast, especially in wet conditions. The non-woven geotextile also prevents the fines moving up from the capping and subgrade layers, thus keeps the recycled ballast relatively clean.

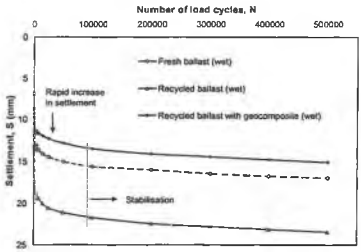

Fig. 20 Settlement of Fresh Ballast and Recycled Ballast with and without Geosynthetics (Wet Samples)

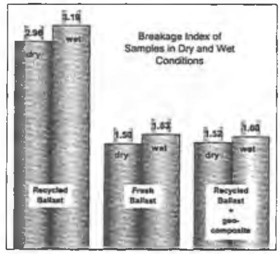

Fig. 21 Breakage Index of Fresh Ballast and Recycled Ballast with and without Geosynthetics

To quantify ballast breakage based on Marsal's (1973) method, each ballast specimen was sieved before and after testing and the changes in percentage retained on each sieve size, were recorded. The breakage index values of fresh and recycled ballast with and without inclusion of geocomposites are shown in Fig. 21. This figure clearly depicts the benefits of using geosynthetics in the reduction of recycled ballast breakage in both dry and saturated conditions.

Effect of Particle Size Distribution

The gradation of ballast is a prime consideration for in-track performance of ballast. The gradation should provide the measures to develop the density requirements and the adequate shear strength for the ballast layer, as well as to provide the necessary porosity to allow proper run off groundwater. Higher shear strength of ballast and increased track stability can only be obtained at the expense of ballast drainage capability. The optimum ballast gradation needs a balance between the uniform and broad gradations.

According to previous investigations on ballast gradation (e.g. Jeffs and Marich, 1987; Raymond, 1985; Chrismer, 1985; Selig and Waters, 1994) well-graded ballast, when compared to uniformly graded ballasts, give lower track settlements and produce more stable tracks. A further benefit of well-graded ballast is that it decreases the possibility of ballast/subballast mixing due to the occupation of ballast voids by finer particles. Although well-graded distributions increase the ballast life, they have reduced permeability and a greater risk of fouling due to the smaller void spaces, especially if the source of fouling is from ballast wear due to coal carrying trains. Well-graded distributions are also more likely to segregate during transportation and installation, making in-track gradation harder to control.

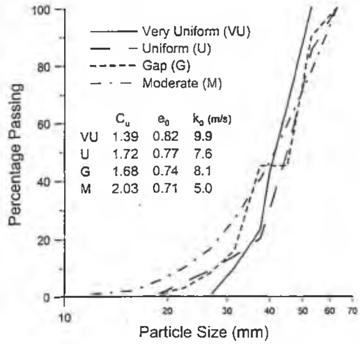

Fig. 22 Particle Size Distributions Used in Triaxial Tests, along with their Uniformity Coefficients, C_u, Initial Void Ratios, e_0 and Permeability Coefficients, k_0 (Indraratna et al., 2004)

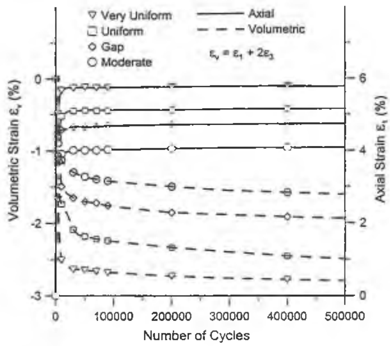

Fig. 23 Axial and Volumetric Strain Response of Different Distributions under Cyclic Loading (Indraratna et al., 2004)

To evaluate the effects of particle size distribution on deformation and degradation behaviour of ballast, large-scale cyclic triaxial tests were conducted on four different distributions of latite basalt at University of Wollongong. Details of the testing apparatus, can be found in Indraratna et al. (2003). It is known that well-graded aggregates can be compacted to higher densities than uniform specimens. Therefore, specimens were compacted to equivalent heights using a fixed compaction time, hence, the specimens varied in initial density and void ratio. The gradation and void ratio characteristics of the test specimens are shown in Figure 22. Samples were subjected to an effective confining pressure of approximately 45 kPa. To simulate the train axle loads running at relatively high speed, cyclic loading with a maximum deviator stress of 300 kPa was applied on the ballast specimens at a frequency of 20 Hz.

Figure 23 shows the effects of grain size distribution on the axial and volumetric strains of ballast under cyclic loading. The test results reveal that most uniform to moderately uniform samples give higher axial and volumetric strains. This is attributed to the looser states of the specimens prior to cyclic loading. In contrast, gap-graded and moderately graded distributions provided denser packing with a higher co-ordination number. Therefore, these gradations provided higher shear strength and thus, decreased the settlement. Figure 24 illsutrates the relationship between the uniformity coefficient (C_u) and particle breakage. The test results indicate that ballast breakage decreases as the value of C_u increases, with the exception of the gap-graded specimen. The gap-graded ballast excluded particle sizes, which were found to be highly vulnerable to breakage by previous research (Indraratna et al., 2001). Therefore, the gap-graded specimen shows a smaller amount of breakage than the uniform and very uniform gradations.

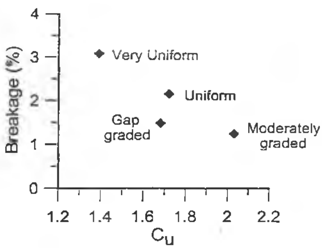

Fig. 24 Effect of Grading on Particle Breakage (Indraratna et al., 2004)

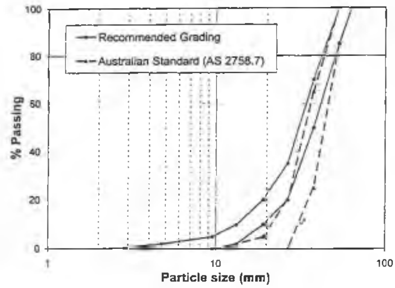

Fig. 25 Recommended Railway Ballast Grading in Comparison with the Current Australian Standard Grading Requirements (Indraratna et al., 2004)

As Fig. 25 indicates, the initial permeability (k_0) according to Hazen's formula would drop by approximately 50% if the moderately graded distribution were employed instead of the very uniform distribution. However, in the absence of fouling, the moderately graded ballast is still considered to be sufficient for track drainage. Moreover, in terms of deformation and resistance to particle breakage, moderately graded ballast is far superior to uniform gradation, which is used in the current ballast specifications of many countries including Australia.

The cyclic test results of ballast varying the gradation indicate that even a modest change in the uniformity coefficient (C_u) substantially affects the deformation and breakage behaviour of ballast. The test results suggest that a distribution similar to the moderate grading would give improved track performance. Based on these findings, Indraratna et al. (2004) recommended the ballast gradation with a uniformity coefficient exceeding 2.2, but not more than 2.6 as most appropriate. This recommended gradation, which is relatively more well-graded than the current Australian Standard (AS 2785.7, 1996), is presented in Figure 25. The authors feel that a less uniform ballast gradation such as this is also suitable to be used for the tracks in Sri Lanka during reconstruction.

As discussed in previous sections, it is recommended to reuse the existing ballast of rail tracks in the devastated areas to reduce the rehabilitation cost and time. The findings indicate that modifying the particle size distribution of ballast in reconstruction work can be considered as another approach, in conjunction with the inclusion of geosynthetics, to reduce the recycled ballast breakage and to increase its shear strength.

Effect of Confining Pressure

The confining pressure acting on ballast layer has not often been considered as a significant factor in conventional rail track design. This is because the confining pressure applied on the tracks by the shoulder ballast and sleepers is small in comparison with the relatively high vertical stress. The role of confining pressure on ballast performance under cyclic loading has been investigated by Indraratna et al. (2004; 2005) to evaluate whether there is an optimum confining pressure in the track to reduce the amount of ballast breakage.

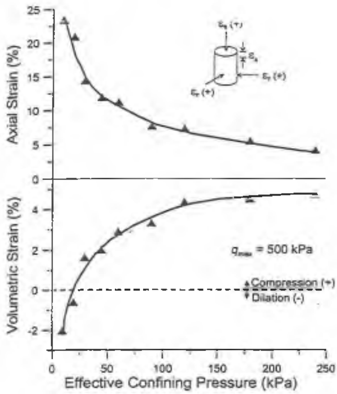

Fig. 26 Variation of Axial and Volumetric Strains with Confining Pressure (Indraratna et al., 2005)

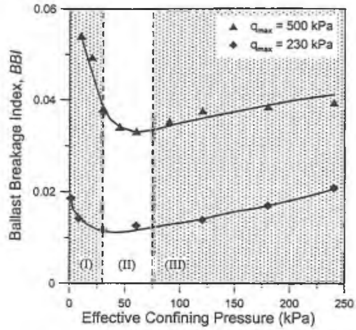

Fig. 27 Effect of Confining Pressure on Particle Degradation (Indraratna et al., 2005)

The triaxial testing procedure was similar to that outlined for the particle size distribution tests. Specimens were prepared with the same gradation and initial porosity (i.e. d_{50} = 38.5 mm, C_u = 1.54. e_o = 0.76). Effective confining pressures (σ_3') ranged from 1-240 kPa. Figure 26 illustrates the effect of confining pressure (σ_3') on the axial and volumetric strains achieved at the end of 500,000 cycles for the maximum deviator stress, q_{max} = 500 kPa (Indraratna et al., 2005). As expected, the axial strains decreased with the increasing confining pressure. Ballast specimens exhibited dilation at small confining pressure ($\sigma_3' < 30$), but became progressively more compressive as the confining pressure increased from 30 to 240 kPa.

The effect of confining pressure on particle degradation is shown in Figure 27. The sample breakage has been divided into three regions namely: (I) dilatant unstable, (II) optimum and (III) compressive stable degradation zones (Indraratna et al., 2005). At low confining pressure of region (I) where σ_3' <30 kPa, ballast specimens are subjected to rapid and considerable axial and expansive radial strains. This leads to an overall volumetric increase or dilation. In this region, particles do not have sufficient time to rearrange, and due to the excessive axial and radial strains, considerable degradation occurs via shearing and attrition of angular projections. Because of the small confining pressures applied here, specimens in this degradation zone are characterized by a limited co-ordination number as well as relatively small particle-to-particle contact areas. As the confining pressure is increased to the middle (optimum) region (σ_3' = 30-75 kPa), axial strain rate is greatly reduced due to increased apparent stiffness. It is noted that the overall volumetric behaviour is slightly compressive. In this region, particles are held together in an optimum array with sufficient lateral confinement so as to provide an optimum contact stress distribution and increased inter-particle contact areas. This results in the reduction of the risk of breakage associated with stress concentrations. As σ_3' is increased further to the compressive stable region (σ_3' > 75 kPa), particles are forced to move against each other within a limited space for sliding and rolling. Therefore, breakage is significantly increased. In this region, particles fail not only at the beginning of loading when the axial strain rates are the greatest, but also by the process of fatigue as the number of cycles increases.

Fig. 28 Track Buckling due to Stress Build up in the Welded Rail as a Result of Heat and Insufficient Lateral Stability to Hold the Track

The role of confining pressure will be more significant on curved tracks with elevated temperature fluctuation. The lateral force produced by continuously welded rail on a curved track depends on the train speed, the axle load, the temperature changes, curvature of the track (degree of the curve) and the slope of the track. Figure 28 indicates the buckling of the track due to the build up of stress in the welded rail as a result of high temperature change and insufficient lateral stability (confinement) to support the track.

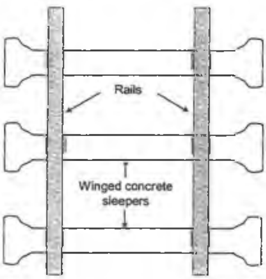

Fig. 29 Sleepers with Enlarged Ends to Increase the Confining Pressures

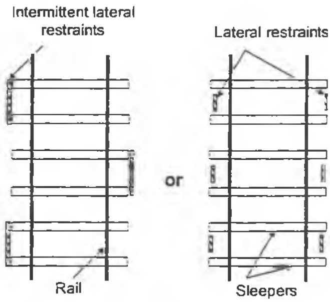

Fig. 30 Increasing Confining Pressure Using Intermittent Lateral Restraints

Some measures for increasing track confinement include:

(1) Reducing sleeper spacing
(2) Increasing height of shoulder ballast
(3) Inclusion of a geosynthetic layer at the ballast-subballast layer interface
(4) Altering the shape of sleepers at both ends (Figure 29)
(5) Using intermittent lateral restraints at various parts of the track (Figure 30)

CONCLUSIONS

Sri Lanka, among several other countries, was devastated by the Indian Ocean tsunami, which occurred on 26th December 2004. In Eastern and Southern Provinces of Sri Lanka the transported fine marine sediments mixed with the surface soils under turbulent conditions of the tsunami waters, which upon receding settled in a relatively loose state compared to the originally compacted surface densities. The rail tracks built on sandy soils were totally uplifted in some areas as the formation soils were subjected to piping, or softened or scoured. In this paper, the recommended procedures and suggestions that can be adopted for reconstruction of rail track substructures in the affected costal soils have been explained.

Based on the preliminary site investigation conducted by the first author, reconstruction of the rail track requires appropriate improvement of the subgrade soils. Reducing the void ratio to at least 0.45 is necessary to achieve an adequately stiff surface layer prior to placing the ballast and subballast. Various compaction techniques for loose sand were discussed. In addition, ground improvement techniques for soft soils were presented, including the use of prefabricated vertical drains (PVDs). The guidelines for dwelling reconstruction in the Tsunami affected areas were proposed including housing location and foundation design.

To accelerate rail track rehabilitation, selected waste ballast in tsunami-affected areas, when properly cleaned and stabilized with geosynthetics can be reused as load bearing materials. The use of composite geosynthetics at the bottom of the recycled ballast layer is highly desirable due to the heterogeneously mixed soils along the track. Based on extensive research at University of Wollongong, it is expected that the use of bonded geogrids-geotextiles will reduce differential settlements of the track apart from increasing the overall resilient modulus of the layered stratum, where the surface soil properties of the disturbed ground may be both variable and unpredictable even after compaction along the track. Geocomposites also decrease track lateral movement, ballast degradation and subgrade pumping as discussed.

It is illustrated that the gradation of ballast plays a significant role in the strength, deformation, degradation, stability and drainage of tracks. Well-graded ballast gives denser packing, better frictional interlock and hence, lower settlement. On the other hand, almost all ballast specifications demand uniform gradation for free draining. However, the uniformly graded ballast gives higher settlement and also more vulnerable to breakage than well-graded ballast. Test results indicate that the use of slightly broader graded ballast than the current Australian Standard gives considerably lower settlement and decreases the extent of breakage while not affecting drainage significantly. From a drainage point of view, this gradation has sufficient permeability and is acceptable for track substructure as long as the ballast is free of fines and an appropriate drainage system is constructed along the track. It is recommended that the rail tracks in Sri Lanka adopt a less uniform ballast gradation based on these findings. Another factor that affects the performance of ballast is the track confining pressure. Findings based on large scale triaxial testing indicate that a small increase in confining pressure ($\sigma_3' =$ 30-75 kPa) improves the track stability with less ballast degradation. This range of confining pressure results in enhanced particle contact areas adopting a more favourable internal stress distribution (less stress concentrations that induce fracturing).

In brief, reconstruction of washed-away tracks in tsunami-affected areas requires detailed investigation, risk assessment and effective measures to improve the clearly disturbed soils. The approaches introduced and recommended in this paper are cost-effective and not time consuming. The field techniques can be applied through the available equipment in Sri Lanka, without unnecessary sophistication.

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