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Reconstruction Methods for Tsunami Affected Coastal Soils with Special Reference to Low-Cost Dwellings and Rail Tracks

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Abstract: The Boxing Day tsunami in December 2004 devastated several South and Southeast Asian countries. In the Eastern and Southern coastal belt of Sri Lanka, the floodwaters caused unprecedented damage to infrastructure and over 40,000 fatalities. Widespread destruction included severe damage to many buildings and dislocation of several kilometres of rail tracks. Under excessive hydraulic gradients of waves, the geotechnical properties of surface soils up to a meter or more have been significantly altered. In this paper, the relevant aspects of dwellings and rail tracks and reconstruction on devastated coastal soils are elucidated. Guidelines for reconstructing robust cost-effective foundations are discussed, based on the first author’s own experience. Revised ballast grading and enhanced track conditions are considered, including the benefits of increasing track confining pressure and the essential need for soft formation stabilisation. The use of geocomposites in achieving reduced track settlement, increased resilient modulus and decreased ballast degradation, is described.

1 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 20-30 km/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 to a 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.

On 26 December 2004, the largest earthquake for more than 4 decades 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 tsunami 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 700 km/h) 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 (waves up to 13 m), its southern coast (Fig. 1) was severely damaged by the turbulent and rebound waves with considerable angular momentum with heights still reaching close to 10 m. The damage caused by these turbulent waves were so catastrophic that hardly any houses and commercial buildings within a 100-150 m proximity to the shore were spared, 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. More than 1000 passengers lost their lives and many others injured, when the tsunami engulfed a crowded intercity train, derailing, toppling and submerging its carriages, making this train disaster the worst rail accident ever to be recorded. The lifting and piping of the formation soil beneath the track caused rapid demounting of the track, lifting it up with the tidal waters and displacing it several meters.

Site reconnaissance at the location of this train disaster was conducted under the guidance of the first author with the assistance provided by the University of Moratuwa and Engineering Laboratory Services Ltd., Sri Lanka. 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 a result of an earthquake of magnitude 8.1 near Andaman Islands (Wattegama, 2005). This paper will elucidate the need for rebuilding dwellings and 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 instead of conventional methods.
PRELIMINARY SITE INVESTIGATIONS

A trial open pit 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 only a more obvious well-graded nature of the sand closer to the surface, in the areas where the beach sand was known to be very uniform before the tsunami. The uniformity coefficient has changed from 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 down to 10 m deep (Fig. 6), on 2 different locations near the train disaster site. Figs. 7 and 8 illustrate measured parame-
ters obtained from the 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 1 m was completely remolded by flooding.

Fig. 7. Cone penetration test results of soil layers (CPT) after tsunami occurrence (Site 1).

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) sediments 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.

Table 1. Soil properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (h)</td>
<td>600 mm</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Water content (w %)</td>
<td>12%</td>
<td>17%</td>
</tr>
<tr>
<td>Dry density (ρ_d)</td>
<td>1593 kg/m^3</td>
<td>1690 kg/m^3</td>
</tr>
<tr>
<td>Void ratio (e)</td>
<td>0.68</td>
<td>0.59</td>
</tr>
<tr>
<td>Degree of saturation (S_s)</td>
<td>47.3%</td>
<td>77.2%</td>
</tr>
</tbody>
</table>

Fig. 8. Cone penetration test with pore pressure (CPTU) results 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).

Fig. 10. Protection from tree line.

Fig. 11. Housing construction on raised earth platform.

The soil properties of two soil samples in tsunami-affected area (Fig. 9) are given in Table 1. The void ratio of sample 1 has been about 0.7 at 600 mm depth, 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:

\[ i_{cr} = \left( \frac{\gamma_s - 1}{\gamma_w} \right) \approx 1.14 \]  

where, \( \gamma_s \) = unit weight of saturated soil and \( \gamma_w \) = unit weight of water. The above value of \( i_{cr} \) implies that a rapid flood with a height greater than 1 m may induce piping of the shallow surface soils to a substantial depth.
3 RECONSTRUCTION GUIDELINES FOR HOUSING OF 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 design of foundations.

3.1 Locations and alignment of houses

1. Dwellings should be constructed at a ‘safe distance’ of at least 100-200 m away from the beach depending on the area (e.g. 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 remolded 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 0.6-1 m in height, to provide protection against flooding and foundation scouring (Fig. 11).

4. Dwellings may be constructed such that the strong masonry side faces the direction of waves (Fig. 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.

3.2 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 (1-2 m depth) should be stabilised by appropriate ground improvement techniques, as will be discussed later. 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 250 mm wide trenches may be excavated up to 600 mm deep and the
bottom of these trenches compacted to about 95% relative density. Subsequently, a 200-250 mm thick compacted gravel (size 7-10 mm) 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 3 m and at all corners of the dwellings as shown in Fig. 14. These piers may be up to 1.5 m 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).

4 BALLAST AND RAIL TRACK MODIFICATION

Ballast is the largest component of a rail track by weight and volume. While ballast is expected to be低成本 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: distributing of loads received from the sleepers, damping of dynamic loads, producing 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, recycled ballast has lower internal friction angle due to attrition and reduced angularity, hence, exhibiting higher settlement and lateral deformation compared to those of fresh ballast upon cyclic loading. Research at University of Wollongong indicated that inclusion of geosynthetics improves the geotechnical properties of recycled ballast, as discussed later.

4.1 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. 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 these problems if they are selected and 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-needed non-woven geotextiles with weight (mass per unit area) more than 500 g/m², 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 & Jones (2000) have described, geocomposites can provide reinforcement to the ballast layer, as well as filtration and separation functions simultaneously. The combina-
tion 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 non-woven geotextiles are used for separation and filtration, preventing fouling of ballast and providing quick relief of pore water pressures.

4.1 Effect of particle size distribution

The gradation of ballast is a prime consideration for track performance. To evaluate the effects of particle size distribution on deformation and degradation behavior of ballast, large-scale cyclic triaxial tests were conducted on four different distributions of latite basalt at the University of Wollongong. Details of the testing apparatus can be found in Indraratna et al. (2003). The gradation and void ratio characteristics of the test specimens are shown in Fig. 17. Samples were subjected to an effective confining pressure of approximately 45 kPa, and cyclic loading having a maximum deviator stress of 300 kPa was applied on the ballast specimens at a frequency of 20 Hz. Fig. 18 shows the effect of grain size distribution on the axial and volumetric strains of ballast under cyclic loading. The tests 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 coordination number (increased surface contact). Therefore, these gradations provided higher shear strength as well as reduced settlement.

In terms of deformation and resistance to particle breakage (Fig. 19), the test results indicate that moderately graded ballast is far superior to uniform gradations, which is now acknowledged in the current ballast specifications of some countries including Australia. The test results also indicate that moderately graded ballast is still porous enough to maintain sufficient track drainage. Based on these findings, Indraratna et al. (2004) recommended a ballast gradation with a uniformity coefficient exceeding 2.2, but not more than 2.6, in comparison to very uniform (conventional) grading with \( C_U = 1.4-1.5 \). This recommended gradation, which is relatively more well-graded than the current Australian Standards (AS 2758.7, 1996) is presented in Fig. 20.

![Fig. 19. Particle size distributions used in the triaxial tests (Indraratna et al., 2004).](image)

![Fig. 20. Recommended railway ballast grading in comparison with the current Australian Standard (Indraratna et al., 2004).](image)

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The role of confining pressure on ballast performance under cyclic loading has been investigated by Indraratna et al. (2005b). Fig. 21 illustrates the effect of confining pressure \( (\sigma_3') \) on the axial and volumetric strains of ballast achieved at the end of 500,000 cycles for a maximum deviator stress of 500 kPa. 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 Fig. 22. It was found that there is an optimum confining pressure (30-75 kPa) in which the amount of ballast breakage was reduced to its minimum value. Fig. 23 clearly 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. 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. Widening the sleepers at both ends (Fig. 24), and
5. Using intermittent lateral restraints at various parts of the track (Fig. 25).

4.2 Improvement of recycled ballast using geosynthetics

The deformation and degradation behaviour of fresh and recycled ballast was investigated in a large triaxial chamber (Figs. 26 and 27) 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 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. Details of the large-scale rig can be found in Indraratna et al. (2003).

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 (bonded geogrids and non-woven geotextiles). 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. (2004). Only selected results illustrating the effects of inclusion of geocomposites on ballast settlement and breakage are given in this paper.
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 reduce the settlement of recycled ballast considerably, the geocomposites (geogrids bonded with non-woven geotextiles) stabilises recycled ballast remarkably well. As described by Rowe and Jones (2000), geocomposites can provide reinforcement to the ballast layer, as well as filtration and separation functions simultaneously. The combination of reinforcement by the geogrids and the filtration and separation functions provided by the non-woven geotextiles component (of the geocomposites) reduces the lateral spreading and fouling of ballast, especially in wet conditions. The non-woven geotextiles also prevent the fines moving up from the capping and subgrade layers, thus keeps the recycled ballast relatively clean.

To quantify ballast breakage based on Marsal's method (1967), 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 recycled ballast stabilised with geocomposites in dry and wet test conditions were almost the same as fresh ballast (without geocomposites), and approximately 50% lower than those of recycled ballast without geosynthetics (Fig. 30). This indicates clearly the benefits of using geosynthetics in the reduction of recycled ballast breakage in both dry and saturated conditions.

4.2 Subballast 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.

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 is unable to dissipate excess pore pressures quickly enough. This is particularly important in the case of freight trains that are both very heavy and very long.

5 FORMATION SOIL 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 at the site (Indraratna et al., 2005a), 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 subgrade: (a) loose fine sand and (b) soft silty or clayey sediments need special consideration, as they are highly susceptible to failure under cyclic 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 optimum soil improvement, but of course at a reduced train speed. For stabilising the formation soils, a variety of options of ground improvement are available in Sri Lanka. Some selected key means of subgrade enhancement are discussed in this section.

![Fig. 28. Settlement of dry fresh and recycled ballast with and without geosynthetics (Indraratna et al., 2004).](image)

![Fig. 29. Settlement of wet fresh and recycled ballast with and without geosynthetics (Indraratna et al., 2004).](image)

5.1 Loose sandy subgrade

The preliminary site reconnaissance (Indraratna et al., 2005a) 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 (shear strength), thereby reducing the post-construction settlement as...
well as increasing the bearing capacity. The surface vibratory or pneumatic compaction is 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 a tighter state using dynamic forces. In the field, the soil up to 1 m deep can be compacted using rolling and kneading, of impact vibrating and ramming.

Fig. 30. Breakage index of fresh ballast and recycled ballast with and without geosynthetics.

Grouting technology and chemical stabilisation can also be used as alternatives to compaction to retard water seepage and to increase the shear strength of loose sand formations. For preventing formation collapse during significant earthquakes, deep mixing method may be employed to increase the liquefaction resistance of loose sediments beneath rail track and improve its stability.

5.2 Clay subgrade

In the region of the site of soil exploration, no thick layers of soft clays were found (up to 12-15 m depth), but clayey sands and organic sediments will still show significant 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: stabilisation by chemical admixtures; geosynthetic reinforcement; and preloading and the use of prefabricated vertical drains.

1. Stabilisation 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 5-15 m under the rail tracks 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 subgrade 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.

3. Preloading and Vertical Drains: Preloading is one of the most successful ground improvement techniques that can be used in soft soil subgrade. 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.

5 CONCLUSIONS

Sri Lanka, among several other countries, was devastated by the Indian Ocean tsunami, which occurred on 26th December 2004. In this paper, the recommended procedures and suggestions that can be adopted for reconstruction of dwellings (including housing locations and design of foundations), and rail track substructures in the affected coastal soils have been explained. The approaches recommended are cost-effective and not time consuming.

Based on the preliminary site investigation conducted by the first author, reconstruction of the affected areas requires reducing the soil void ratio to at least 0.45 to achieve an adequately stiff surface layer prior to the reconstruction process. Reconstructing low-cost dwellings in the affected coastal areas requires the following guidelines. Dwellings should be constructed at a safe distance of at least 100-200 m away from the beach in such away that the strong masonry side faces the direction of waves. Dwellings should also be constructed on a raised earth platform in the
order of 0.6-1 m in height. Housing in areas behind densely 
grown palm trees is encouraging.

To accelerate rail track rehabilitation, selected waste ballast in 
tsunami-affected areas, when properly cleaned and stabilised 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. Geocomposites also decrease track lateral move-
ment, ballast degradation and subgrade pumping.

It is illustrated that the gradation of ballast plays a significant 
role in the strength, deformation, degradation, stability and drain-
age 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 break-
age while not affecting drainage significantly. It is recommended 
that the rail tracks in Sri Lanka adopt a less uniform ballast gra-
dation 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 (σ’ = 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 fa-
vourable 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 and not time consuming. The field techniques can be 
employed through the available equipment in Sri Lanka, without 
unnecessary sophistication.

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