How to Overcome Geotechnical Challenges in Implementing High Speed Rail Systems in Australia

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ABSTRACT: Although there are a few medium speed rail systems in Australia, there is not a passenger rail transport with the high transit speed, seen in other countries. This paper firstly summarises lessons learnt from other countries, experienced high speed rail (HRS) for many years. Then, the challenges associated with implementing HSR systems in Australia are explained. The main challenges include selection and design of proper tracks, geographical issues, environmental concerns, economics and project costs and construction procedures. The second part of the paper presents the effective solutions to the geotechnical challenges associated with HSR systems. Various approaches are presented to improve the ballast layer properties and enhance the track formation bearing strength, stiffness, resiliency and dynamic properties. Employing concrete slab (ballast-less) tracks is also taken into consideration for HSR systems, and their performance is compared to ballasted tracks.

1. INTRODUCTION

Growing congestion in major cities, increasing population and getting higher commuting across cities, have resulted in massive investment in transport network in Australia. The annual cost of traffic congestion in Australia is estimated at $10 billion apart from an annual road toll of about 1500 and 30,000 injuries (Perry, 2010). Road transport is Australia's third largest source of greenhouse gas emissions. Hence, "business as usual" is no longer an option. Railway and airway systems are other options for faster and safer travels. Obviously air travel offers higher speed than railway. However more time is required for air travels due to boarding (aircrafts have fewer doors than trains), transporting to or from airports, security check, luggage drop and ticket check. In addition, railway stations are usually located nearer urban centres than airports. Rail travel has less weather dependency than air travel and generally they are more comfortable, as passengers can move around the train during the journey. High Speed Rail (HSR) is currently an experienced rail transport technology, which has been demonstrated internationally to deliver real transport benefits against road and air transportation.

Railway forms an important part of the transportation infrastructure of a country and plays an important role in infrastructure sustainability. Australian railway organisations should set down clear strategic directions to direct government and industry to ensure that Australia's rail networks are capable of meeting future transport demands. Recently the Australian Government has been committed to support a comprehensive feasibility study on high speed rail (HSR) systems, by identifying the potential rail corridors, undertaking geotechnical and engineering investigations and carrying out the financial and economic modelling to determine the project's viability. The study shows that HSR has the potential to cut travel times particularly for people commuting between capital cities in the east coast of Australia. According to Department of Infrastructure and Transport (2012), nearly 10 million people live along the east coast between Brisbane, Sydney and Melbourne, hence ongoing investment in modern transport infrastructure is essential.

This paper presents the feasibility and challenges of implementing high speed rail systems in Australia by looking at the main elements that a high speed train is composed of. This paper also reviews the performance of high speed rail systems around the world and the factors contributed to their success. Australia has its own unique demographic, geographic, geological and economic characteristics and the aim is to identify where there are overlaps between Australia's characteristics and countries with high speed rail systems.

Conventional ballasted track systems have reasonably served the railroad industry over the last 150 years. Ballasted track is expected to also serve the needs of the industry in the future years. Various approaches are presented for improving the ballast layer properties including the track stiffness, resiliency, dynamic properties and formation bearing strength. Various aspects of Slab track systems are also discussed in this paper. They will be a key option in construction of new track structures for the use of high-speed passenger trains. In conclusion, the performance of HSR systems employing ballasted tracks or slab tracks is discussed and compared.

2. WORLD EXPERIENCES WITH HIGH SPEED RAIL

High speed rail is a form of mass rail transport that runs at significantly higher speeds than normal rail systems. The approximate maximum commercial speed is 300 km/h for the majority of national high speed railways (France, Spain, Japan, China, Taiwan, Germany, Italy and UK). However, the specific definitions by the European Union include 200 km/h for upgraded tracks and 250 km/h or faster for new tracks (Givoni, 2006). High speed trains travel at their maximum speed on specific tracks or on conventional tracks with standard gauges with avoiding at grade crossing, short radius curves and high gradient (i.e. greater that 2%).

2.1 Asia

Japan was one of the first nations to implement a high speed rail system. Several other Asian countries such as China, South Korea and Taiwan planned and constructed HSR networks.

Japan: In the densely-populated country of Japan, especially the area with 45 million people between Tokyo and Osaka, congestion on roads and rails became a serious problem in the 1950s. The construction of new rail service, named Shinkansen (bullet train) began in 1959 and was completed in October 1964, in time for the summer Olympics in Tokyo (Okada, 2007). The 1960s were a time of great economic growth and prosperity. The first Shinkansen trains have run the 515 km distance with a top speed of 210 km/h and an average speed of 162.8 km/h with stops at Nagoya and Kyoto.

China: In China, plans for the largest high-speed railway network in the world were driven by a combination of capacity constraints on existing lines and a desire to shorten journey times, while promoting development along the route. According to Okada (2007), the construction schedule was significantly accelerated due to additional funding in the stimulus package of 2008 and a number of lines have been due to be completed by 2013. China has recently increased the speed of the existing train lines. Passenger lines now run at speeds over 120 km/h on approximately 22,000 km of track, at speeds greater than 160 km/h on about 14,000 km of track and at speeds greater than 200 km/h even 250 km/h for around 6,000 km of track.

2.2 Europe

In Europe, high-speed rail began during the International Transport Fair in Munich in June 1965, when German Federal Railways operated fast trains with 200 km/h between Munich and Augsburg. The same year, in France, the engineer Jean Bertin invented the Aérotrain, a hovercraft monorail train, and built the first prototype (Gourvish, 2010). The European high speed rail network was initially a series of national lines. In other words, there was no 'European Network'. The proposal for an interconnected network came through the Community of European Railways in 1990 and this became the Trans-European network for high-speed rail. The proposed network initiated for three reasons: (1) overcome bottlenecking, as there was a problem with limited capacity on critical sections of the network, (2) increase speeds, as in some parts of the network, the speeds were too low and (3) improve accessibility to provide access to some remote regions

France: National Corporation of French Railways launched the Train á Grande Vitesse (TGV) program to create a French high speed rail system. Its debut line was launched in 1981 linking Paris and Lyon. Initially the line trains ran at normal speeds but in 1983 the line was fully operational and the journey over 409 km lasted approximately 2 hours.

Germany: In terms of network size, Germany's high speed train, the ICE (Inter-City Express), currently ranks fifth in the world, with about 1,300 km of lines in operation, behind China, Japan, France and Spain. Germany plans, over the next few years, to construct an additional 1,000 km of lines (Givoni, 2006). With over 10 operating lines, the HSR connects many of the country's populated centres and these rails in Germany have an 8.4% share of the passenger transportation market overall. However, most German HSR lines operate at top speeds of 250-280 km/h, somewhat slower than other European countries. As an example, a trip from Berlin to Hamburg, for a distance of 255 km, takes 1 hour and 50 minutes.

United Kingdom: Britain's high speed rail technologies began in 1970s. They, rather than building new tracks, decided to develop rolling stock, which would achieve high speeds on existing tracks. The advanced passenger train (APT) was developed, but was phased out due to technical problems. Those diesel powered trains achieved speeds of up to 238 km/h (Gourvish, 2010). In 2009, High Speed Two Ltd was established; its aim was to develop proposals for a high speed railway link between London and the West Midlands. At present the route serves some of England's most populated cities, including Leeds, Manchester, Birmingham and London.

2.3 Main Models of High Speed Trains

As explained earlier, many countries have adopted the high speed rail as a transport solution. The length of high speed rail around the world has been increased almost exponentially within the last 50 years, as shown in Figure 1. It is increasingly been seen as a more viable transportation solution.

The different needs and special characteristics of different countries pursuing the development of HSR operation have led to the evolution of various models of HSRs. The Japanese Shinkansen, which was the first modern HSR in operation, can be considered as the base model. Subsequently, three other models have evolved according to Givoni (2006).

Shinkansen: It is a complete separation from other rail services. A unique feature of the Shinkansen was the new dedicated line, which in the case of Japan was required, since the conventional railway network had a narrow gauge and could not support the HSR. This isolated the Shinkansen services from the rest of the railway system in Japan. The geographic features of Japan together with the requirement to avoid tight curves and steep gradients (to allow for high speeds) resulted in many tunnels and bridges along the route. A total of 30% of the Japanese Shinkansen lines run through tunnels (Okada, 2007) leading to very high construction costs. Structure breakdown of the Shinkansen lines are approximately: 20% track bed, 10% bridge 30% viaduct and 50% tunnels.

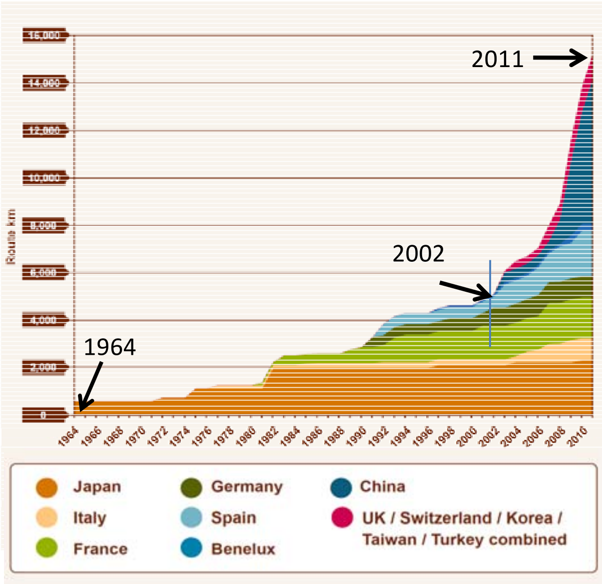

Figure1 Growth (in km) of HSR routes from 1964 to 2011 (after AECOM, 2013, data taken from World Bank)

TGV: The French TGV, which began operation in 1981, resembles the Shinkansen in purpose, but differs in design philosophy. The most significant difference between the TGV and the Shinkansen is probably the ability of the former to operate on conventional tracks as well, which allows the TGV to use the conventional lines as it enters and leaves the city centres, leading to significant cost savings. It also means that the HSR can serve regions with no HSR infrastructure and specifically serve parts of the network where at present the demand is not high enough to justify the construction of dedicated lines. Germany's high speed train, the ICE (Inter-City Express), follows the TGV model, mainly in the compatibility feature. It deviates from the TGV and the Shinkansen models by adopting a mixed-use line, meaning the line is used for both passenger and freight transport. This feature turned out to be a disadvantage since it led to high construction costs (to support the higher load of freight trains) and low utilisation of the lines, since freight trains operate at much lower speeds.

Tilting System: On many routes, demand is not high enough to justify the cost of constructing new tracks that allow high-speed operation. This problem was solved by the tilting train model, but at the price of lower speeds. To allow higher speeds on conventional lines with tight curves, the train tilts as it passes through curves. By simply tilting the train in tight radius curves, the discomfort that passengers may feel from the centrifugal force, as the train goes at high speed through curves, is solved. The bogies remain firmly attached to the rails, while the body of the carriage tilts, and hence compensates for centrifugal force. This principle is adopted by many countries as a cheaper alternative to the TGV and Shinkansen models. The Swedish X-2000 and the Italian (ETR-450) are running on conventional rail using the tilting mechanism, thus avoiding the price of expensive new tracks, but reaching a maximum speed of 210 km/h (X-200) or 250 km/h (ETR-450). Today, a tilting mechanism is also used on TGV trains and all the new Shinkansen models.

Maglev System: Magnetic levitation (Maglev) technology was first tested in the 1970s, but it has never been in commercial operation on long-distance routes. The technology relies on electromagnetic forces to cause the vehicle to hover above the track and move forward. In practice, the aim is for an operation speed of 500 km/h. In 2003, a Maglev test train achieved a world record speed of 581 km/h. The special infrastructure required for Maglev trains means high construction costs and no compatibility with the railway network. The Maglev is mostly associated with countries like Japan and Germany, where Maglev test lines are in operation. In China, a short Maglev line was opened in December 2003 connecting Shanghai Airport and the Pudong a financial district in Shanghai, with trains running at maximum speed of 430 km/h.

3. IMPLEMENTING HIGH SPEED RAIL SYSTEM IN AUSTRALIA

Australia is far behind Europe, Japan, China and many emerging economies by failing to build a high speed rail network connecting the mainland capitals. According to Wright (2009), a fast train network can stimulate Australian domestic construction sector, provide many jobs, whilst being a major step forward to avoid the looming oil and climate crises. High speed rail projects in Australia have been under investigation since early 1980s. The fastest trains in Australia have a maximum speed of 160 km/h, significantly below the internationally accepted speed for HSR of 200 to 300 km/h. On the other hand, many experts believe that the long distances and difficult terrain between major population centres, low population density of inter-urban regions, and present affordability of air travel have made it difficult for HSR proposals to demonstrate financial viability (Arup-TMG, 2001). However, HSR competitiveness is expected to increase with future population increases, particularly in regional areas.

3.1 Previous Studies

A number of major studies have been conducted for implementing a high speed rail system in Australia:

CSIRO 1984: CSIRO chairman, Dr Paul Wild spearheaded a study for a high speed rail link between Sydney and Melbourne via Canberra, Cooma, Orbost and Latrobe Valley. Its basis was the TGV technology of the time. The conclusion was that the project was deemed to be uneconomic after the cost estimation was found to be enormous, almost AUS$1.5 billion (Williams, 1998).

The Very Fast Train (VFT) Joint Venture 1986: A group comprised of TNT, Elders IXL and Kumagai Gumi proposed a high speed line from Sydney to Melbourne via Canberra. Numerous feasibility studies were done and there was interest from then Prime Minister Bob Hawke. Eventually the proposal was scrapped after a rejection of a taxation to fund the project in 1991 (Williams, 1998).

Speed Rail proposal 1993: Speed rail Pty Ltd proposed a similar route to the VFT corridor limiting it to Sydney to Canberra. It proposed a AUS$2.4 billion line without changing tax laws. Changes were made from standard high speed rail technology to the cheaper tilt trains. After much debate about cost and expenditure, tenders were requested and four international joint ventures submitted proposals. In December 2000, it was decided that the Speed Rail proposal would not proceed due to funding issues (Canberra Business Council, 2008).

Strategic study on implementation of HSR network, Phase 1 and Phase 2: The phase 1 of study (AECOM,2011) short listed a number of corridors along the east coast of Australia. It looked at linking Brisbane to Melbourne via Sydney, Canberra as well as numerous regional areas. The report recommends land acquisitions along the corridor before land costs escalate. Phase 2, in 2013, looks at the financial feasibility of the high speed rail system and identifies an optimum route (AECOM, 2013). Figure 2 presents the proposed HSR routes.

3.2 High Speed Rail Study Routes

A strategic study on implementation of a high speed rail network on the east coast of Australia was announced by Australian Government in August 2010. Accordingly a broad study called Phase 1 assessment, conducted by AECOM in 2011, defined a recommended study area for a further detailed study. Other companies involved in preparation of the study were Grimshaw, KPMG and SKM. The recommended line passes through the east coast of Australia along a coastal route between Sydney and Brisbane, via Newcastle, and an inland route between Sydney, Canberra and Melbourne. The report has declared that the short-listed corridors have generally lower capital costs for infrastructure and property acquisition than other options. The short-listed corridors broadly follow the alignment of the existing long-distance rail network. This could provide opportunities to rationalise or replace regional rail services with high speed rail services on inter-city and regional routes. The short-listed corridors minimise potential impacts on national parks and other sensitive lands. The risk-adjusted cost estimate for the implementation of an overall high speed rail network would fall within the range of $102 billion to $127 billion (in 2012 term).

Figure 2 The recommended high speed rail routes for Australia (after AECOM, 2013)

The key findings of this report, based on the preliminary work undertaken as a part of the study's first stage are (AECOM, 2013):

- Trains would run at an average of 250 km per hour up to a maximum of 350 km per hour on a dedicated track.
- The estimated cost of the network is $114 billion (in 2012 term), comprising $64 billion between Brisbane and Sydney and $50 billion for the Sydney, Canberra and Melbourne section.
- Project involves building and laying more than 1,700 km of new standard-gauge, double-track (approximately $70 million/km)
- Achieve speeds of up to 350 km/h and offer journey times as low as 3 hours from Sydney to Brisbane, and just 40 minutes from Sydney to Newcastle (see Table 1 for more details).
- Between 46 million and 111 million passengers are forecast to use HSR services for intercity and regional trips, if the preferred HSR network were fully operational in 2065, with a central forecast of 83.6 million passengers per year.
- Offer competitive ticket prices, with one way fares from Brisbane to Sydney costing $75-$177; Sydney to Melbourne $99-$197; and $16.50 for daily commuters between Newcastle and Sydney.
- Cut carbon pollution, with emissions per passenger a third of what a car emits. It is assumed that each full train with 450 passengers would be equivalent to taking 128 cars off the road.

Table 1 Proposed HSR study routes
(data taken from AECOM, 2013)

High Speed Rail Routes	Distance (km)	Travel Time
Melbourne - Sydney	824	2h, 44min
Canberra - Sydney	280	64min
Sydney - Newcastle	134	39min
Sydney - Brisbane	797	2h, 37min
Brisbane - Newcastle	662	2h, 28min

3.3 Challenges Associated with High Speed Rail in Australia

Australia has a number of challenges opposing its implementation of a high speed rail system. The geographic conditions of Australia have made the construction of a HSR line difficult and costly for two main reasons, the mountainous terrain and the vast distances that would need to be covered. Compared to other nations, which have implemented a high speed rail system, the population and the population densities of Australia and its cities are relatively small. However, the number of passengers, who use public transportations in some Australian cities is quite high by international comparisons. The main difficulty that Australia faces, similar to most other nations, is the cost of the lines. The failures to implement the proposals recommended in previous studies have mainly been due to the lack of financial feasibility. Although Australia is well placed economically at this point in time, the length of the line would result in a very high construction cost. The number of commuters would take some time to build up and the required rate of return on the asset may not be achieved for number of years.

Topographical Issues: Australia has no large mountain ranges, such as in Japan or Europe. However, HSRs require very long radius curves and low gradients (generally not greater than 1.5%). Key challenges include the western approach to Canberra through the Brindabella Ranges, the northern exit from Sydney through Kuring-gai Chase National Park and across Broken Bay, the Great Dividing Range near Armidale, and the Border Ranges on approach to Brisbane (Arup and TMG, 2001). Viaducts and tunnels will be required for these areas passing through undulating countryside.

Environmental Impacts: High speed rail system has also been advocated by many organisations as it will cut greenhouse gas emissions, primarily by reducing air travel. In Australia, air travel accounts for the highest greenhouse gas emission per passenger (240g CO_2/km) followed by automobiles at 225g and buses at 75g. If powered by existing coal power infrastructure, HSR is predicted to emit 150 g per passenger/km, but this could be reduced to 40g by powering the system with either renewable energy (Canberra Business Council, 2008). The impact of the railway on sensitive environmental areas such as national parks and wetlands has also been an issue. It is clear that any HSR line along the east coast of Australia will necessarily have to pass through national parks and other areas of high environmental and cultural values.

Costs of the Project: As stated earlier, according to the Australian Government's 2013 High Speed Rail Study: Phase 2, the estimated cost of constructing the preferred HSR alignment in its entirety would be about $114 billion (in 2012 terms). It is unlikely that this proposed Australian HSR system to be viable on a privately funded basis alone. The most likely funding arrangement is therefore either the government as the developer or a public-private partnership.

4. TECHNICAL ISSUES WITH HIGH SPEED RAIL SYSTEMS IN AUSTRALIA

4.1 Critical Velocity

There are many geotechnical issues surrounding the performance of high-speed trains on ballasted railway tracks. According to Woodward et al. (2012), these issues include critical velocity effects, track vibration and settlement and the performance of critical areas and assets such as switches, crossings and transitions.

Researchers (e.g. Madshus et al., 2004; Galvin et al., 2010) expressed that when train speed increases to a certain level, large deformations can occur on ballasted tracks and the structures around rail tracks will commence to experience vibration. The magnitude of this speed, which is commonly called the critical speed, is not constant. This speed depends on the ballast and the formation engineering properties. According to Woodward et al. (2012), the ratio of train speed to the ground's natural velocity (i.e. Rayleigh wave velocity) is used to evaluate the dynamic interaction between the train and the track. The Rayleigh wave velocity (V_R) can be determined using the following equation:

$$V_R = (0.87+1.12\,\nu)\,V_s / (1+\nu) \quad (1)$$

where, ν is the Poisson's ratio and V_s denotes the shear wave velocity, which can be found based on Eq (2).

$$V_s = [E / (2\,\rho\,(1+\nu))]^{0.5} \quad (2)$$

In this equation, E is the Young's modulus and ρ is the density of the soil medium. Table 2 summarises different conditions that may occur on tracks for different train speeds (V_T) and critical velocities (V_R). The track will experience large deflection and associated ground vibration, if the train speed is greater than the critical velocity (i.e. the super critical condition).

New engineering studies have been commenced for very high-speed commercial services, particularly in the area of critical velocity or hunting. Hunting is the phenomenon of dynamic oscillation of the bogies, occurring at high speed and leads to dynamic instability and possible derailment. One solution to this problem is the use of yaw dampers and this may increase the safe running speed up to 300 km/h. Yaw dampers are used in locomotives and rolling stock in order to control the rotational movements of the bogie around its vertical axis.

Table 2 Dynamic conditions of rail tracks
(after Yang et al., 2003)

Ratio	Condition
$V_T/V_R < 0.5$	Sub-critical condition
$0.5 \leq V_T/V_R < 1$	Transitional condition
$V_T/V_R \approx 1$	Critical condition
$V_T/V_R > 1$	Super critical condition

4.2 Various Approaches for Ballasted Track Stabilisation

Ballast breaks down and deteriorates progressively under the high train speed, settles differentially due to weak subgrade and poor drainage, fouls due to clay pumping and ballast breakage, and rail tracks buckle due to lack of confining pressure. Ballasted track formation plays a vital role in providing sound track geometry and stability. Many existing tracks in coastal areas in Australia can cause drastic track settlements, as their formation strength will not be sufficient to carry the cyclic loads imposed by the fast trains. If formation is built up of soft or marginal soils, it can become unstable either in a progressive manner or all of a sudden occasion. Progressive shear failure is more likely to occur, which leads to rapid track geometry degradation when exposed to high speed and axle loads by rolling stock traffic. To overcome or reduce the critical velocity issues on ballasted tracks, different mitigation strategies can be adopted. A number of common effective approaches include (1) avoiding poor ground during the planning stages, (2) track reinforcement using geosynthetics, (3) chemical and physical stabilisation of formation to increase bearing capacity, stiffness, resiliency and dynamic properties of the formation, (4) employing prefabricated vertical drains (PVDs) in low-lying areas with high volumes of plastic clays, (5) using native vegetation in semi-arid climates and coastal regions of Australia, (6) selection of high quality ballast with appropriate properties to reduce ballast breakage, (7) providing enough confining pressure and using sufficient shoulder ballast, (8) providing efficient drainage systems and using proper subballast and (9) using shock mats such as elastic pads or rubber mats, to reduce ballast breakage. More details can be found in Indraratna et al. (2012, 2011, 2007, 2006), Lieberenz and Weisemann (2002), Indraratna and Khabbaz (2008), Fatahi et al. (2008, 2011) and Fatahi and Khabbaz (2011).

A considerable length of the proposed HSR route for the east coast of Australia will be located in the low lying coastal areas with soft soil formation. Hence, to avoid costly rail track maintenance including ballast cleaning and replacement, it is essential to quantify ballast behaviour accurately and employ effective stabilisation approaches for track formation.

4.2.1 Inclusion of Geosynthetics

Geosynthetics can be used in railways for drainage, separation and reinforcement. Several works in the literature report reliable performance of geosynthetics in these applications and relevant aspects that must be considered (Selig and Waters, 1994; Raymond, 1994; Indraratna et al., 2011, Fatahi et al., 2011, for instance). A wide range of geosynthetics with different properties have been developed to meet highly specific requirements corresponding to various uses in new rail tracks and track rehabilitation for more than three decades. Enhancing the performance of rail tracks by composite geosynthetics is now extensively considered by rail industry. Based on relatively low cost and the proven performance of geosynthetics in a number of railway applications, many researchers (e.g. Raymond, 1994; Indraratna et al., 2011; Lieberenz. and Weisemann, 2002; Indraratna and Khabbaz, 2008) have conducted experimental programs, field studies and numerical analysis to investigate the effects of the different types of geosynthetics on ballast degradation and fouling, track settlement and stabilisation of railway formation. Geotextiles are widely used as a strengthening and separation materials. Geotextile are usually placed on the subgrade and geogrids (or geocomposites) can be set between subballast and ballast layers. The fundamental and experimental studies (e.g. Indraratna et al. 2006) proved that geogrids bonded with a drainage fabric (geotextiles) will increase the load bearing capacity of the ballast bed, while minimising the lateral movement of ballast and reducing degradation. Use of the composite geosynthetics also prevents the occurrence of liquefied soil (slurry) and its upwards pumping that would foul the ballast.

4.2.2 Using Vertical Drains

Under railway tracks, where the significant amount of the applied load is typically sustained within the several meters of the soil surface, sufficient ballast and subballast depths are provided. In this regard, relatively short prefabricated vertical drains may be adequate in design. Short PVDs (4-8m) can dissipate the cyclic pore pressures, curtail the lateral movements and increase the shear strength and bearing capacity of the soft formation to a reasonable depth below the subballast. The exact required length of PVDs can be determined based on design loads, and soft clay deposit thickness and properties. Using vertical drains will provide a “stiffened” section of the soft clay up to several meters in depth, supporting the rail track within the predominant influence zone of vertical stress distribution. If excessive initial settlement of deep estuarine deposits cannot be tolerated in terms of maintenance practices, the rate of settlement can still be controlled by optimising the drain spacing and the drain installation pattern. In this way, while the settlements are acceptable, the reduction in lateral strains and gain in shear strength of the soil beneath the track, improve its stability significantly. Indraratna et al. (2011) showed that PVDs can effectively speed up the excess pore pressure dissipation and limit the lateral displacement induced by the cyclic loads

4.2.3 Green corridors

Tree roots can be an effective form of natural soil reinforcement apart from dissipating the excess pore water pressure, and generate sufficient matric suction to increase the shear strength of the surrounding soil. In Australia, various forms of native vegetation grow along rail corridors. Tree roots provide three independent stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing matric suction increasing the soil shear strength. The matric suction established in the root zone propagates radially and contributes to ground stabilisation near the root zone. Using native vegetation in semi-arid climates and coastal regions of Australia has become increasingly popular for stabilising railway corridors built over expansive clays and compressive soft soils. As a consequence of passage of heavy trains or ballast tamping to reshape and level the ballast, a ballast bowl (or ballast pocket) in which water accumulates and softens the ground can be formed under the track granular layer. In order to quantify pore pressure dissipation and induced matric suction generated by transpiration, Fatahi et al. (2009) carried out a finite element analysis using ABAQUS software. More details about the model can be found in Fatahi et al. (2009). This type of formation improvement highly depends on type of soil, trees and climate.

4.2.4 Physical and Chemical Stabilisation

Several remedial measures are available to strengthen subgrade materials. The common hydraulic binding agent is lime in particular for stabilisation of soft clay formation. Using lime can substantially increase the stability and load-bearing capacity and decease permeability of the subgrade. Other chemical agents are cement, fly ash, mixture of fly ash-cement or lime, lignin (a by product of paper manufacturing containing wood sugar and lignosulfonate), blast furnace slag-modified grouts and bitumen. Optimising the percentages of applied chemical agent to soil and the ratio of water to agent are essential for a successful stabilisation. Other key aspects in employing pozzolanic stabilisers are the type of the reactive soil, mix design protocol and construction practices. The sulphate content of the soil, or more importantly the lack of sulphates, is critical. The presence of excess sulphate in formation results in unacceptable heave.

During the past 25 years, several railroad companies and the asphalt paving industry have developed optimum or recommended designs and applications for using a layer of hot-mix asphalt within the track structure in lieu of conventional granular subballast. The hot-mix asphalt is designed similar to the bottom layer of perpetual highway pavement. It is designed to be a medium modulus, flexible, low voids, fatigue resistant layer that will accommodate high tensile strains without cracking. The results of the testing program conducted by Rose and Lees (2008) showed that the asphalt binders and hot-mix asphalt do not exhibit any indication of excessive hardening, brittleness, weathering, deterioration or reduction in fatigue life after many years in the insulated track-bed environment.

One of the physical stabilisation methods of weak soils is stone column construction, which involves the partial replacement of weak soil with compacted vertical columns of stone, behaving as in-situ reinforcement of soft soil. The advantages of this method are: increased bearing capacity, reduced settlement, accelerated consolidation, improved slope stability and liquefaction control. The presence of stone columns would transform the ground into a composite mass of granular cylinders. The composite ground can have a lower compressibility and higher shear strength in comparison to natural soft soil.

4.2.5 Stone Columns

In this study, to investigate the influence of stone columns in conjunction with geosynthetics on deformation of the track due to the trainload, finite element modelling using PLAXIS ver. 9 was employed. The reliability of numerical simulations employing, PLAXIS to the deformation analysis of granular materials and ballasted track has been proven by the authors in their previous publications (e.g. Fatahi and Khabbaz, 2011, Fatahi et al., 2012). The model geometry was established considering a typical ballasted track cross-section with concrete sleepers as recommended on the NSW rail network. Depth of each layer from top to bottom including rail, sleeper, ballast, and sub-ballast were 0.1m, 0.15m, 0.3m, and 0.15m, respectively. The subgrade depth was assumed to be 10m to examine the rail track performance. The gauge length of the track was 1.4m. The track section was modelled using 15 node plane-strain triangular elements. The simulation was conducted using the Plastic Analysis Method in PLAXIS. Standard fixities were selected to create the boundary conditions. The water table was assumed to be just below the sub-ballast layer. The train load was 125 kN/m considering as a typical axle train load of 25 tonne/axle. In passenger HSR the total load is considerably less then heavy freight trains. However, after applying the load factor due to the dynamic component of the load, the axle load can be considered almost the same for the purpose of the numerical analysis.

This simulation as shown in Figure 3 was conducted for two configurations: (i) without geogrid reinforcement, and (ii) with geogrid reinforcement. Two layers of geogrids are placed at the interface between the subgrade and sub-ballast, and sub-ballast and ballast. A tensile strength of 600 kN/m with an initial input stiffness of 6000 kN/m for 10% strain is adopted to simulate the geogrids. Interface elements simulating the interaction between the geogrids, and sub-ballast and sub-grade with the strength reduction factor of 0.75 were included.

Conservatively, the sleeper spacing was taken into account for two dimensional plane-strain analysis using the equivalent material properties. The material properties used have been selected according to the NSW State Rail Authority, Australia, and published literature. Hardening soil model (HSM), was adopted as the constitutive model for ballast and sub-ballast. Both shear hardening (to model irreversible strains due to primary deviatoric loading) and compression hardening (to model irreversible plastic strains due to primary compression in oedometer loading and isotropic loading) were considered.

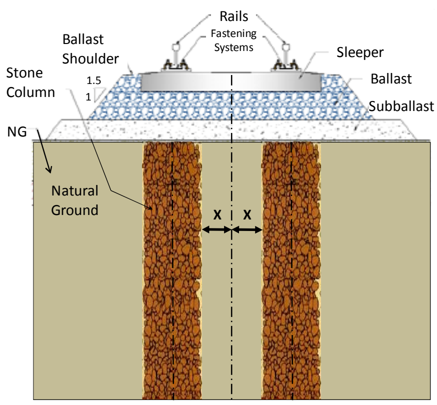

Figure 3 Column pattern to improve railway formation performance

The findings of this research indicate that the cross-sectional configuration of stone columns has a profound impact on the level of soil improvement achieved (Figures 4 and 5). A greater number of columns spaced more closely together at the centre of the track gives a larger level of settlement control. Application of 2 columns is uneconomical to be implemented, when columns are located more than 1m from the track centre. However, it has been observed that using 3 stone columns very close to the centre of the track (i.e. one column at the track centre-line and two under each shoulder) yields only a marginal soil improvement compared to configurations with 2 stone columns. The results also showed that when improved columns are combined with a single layer of geogrids, positioned between the sub-grade and sub-ballast, noticeable gains in settlement control can be achieved. The addition of another layer of geogrids, positioned between the sub-ballast and ballast layers, showed negligible improvement and hence, would not be considered economical for practical applications.

4.3 Slab Tracks

In all high speed rail systems, there is a choice between a slab track system and a ballasted track. Both have their own advantages and shortcomings. Ballast has been used since the beginning of railways in order to serve as the transition element between the sleepers and the formation, providing compliance, and vibration damping, as well as surfacing and draining capabilities to the track. Ballasted degradation is the slow deterioration of the ballast particles due to traffic loading. Ballast breaks down and deteriorates progressively under heavy trainloads, settles differentially due to weak subgrade and poor drainage, fouls by fine particles due to clay pumping and ballast breakage, and rail tracks buckles due to lack of confining pressure. The problems, associated with track foundation, result in costly rail track maintenance including restore the track alignment, ballast cleaning, and ballast replacement (Indraratna et al., 2011; Esveld, 2001). The increased maintenance costs and reduced life cycle of the track associated with higher transportation speeds, axle loads and traffic densities led to the appearance of the slab track in the 1960s.

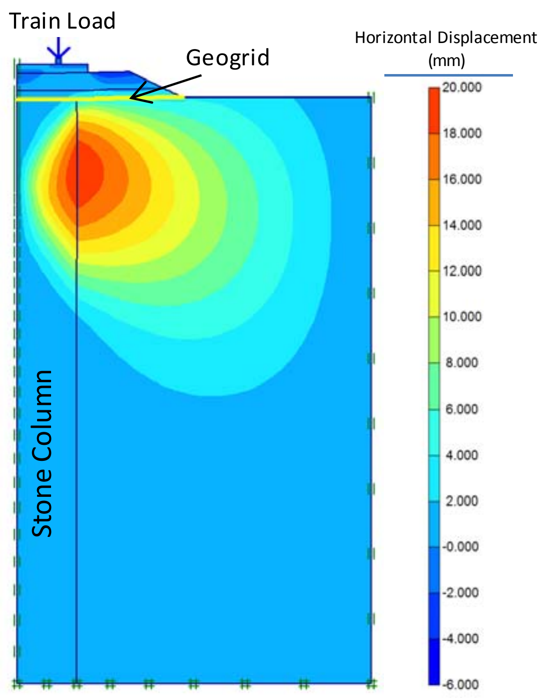

Figure 4 Contours of horizontal displacement for the ground improved using two stone columns offset 500 mm from centre with one layer geogrids

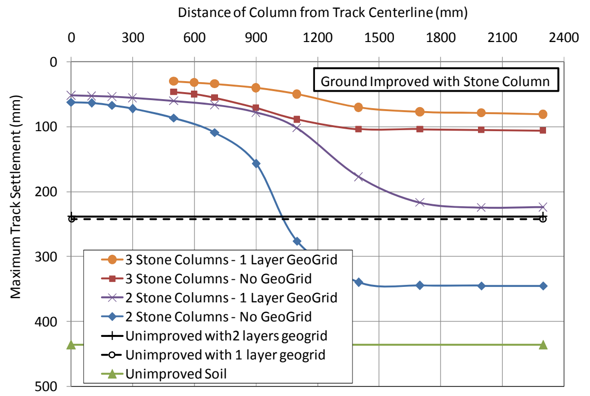

Figure 5 Track settlements with different patterns of stone columns and geogrids inclusion

Some of the advantages of the slab track with respect to the ballasted track are its higher geometric stability and reduced maintenance costs, as well as easier access to the track and evacuation due to the absence of blocking elements between rails. The general benefits of employing slab track can be summarised as follows: (1) reduction of the structure height (2) lower maintenance requirements and hence higher availability, (3) increased service life, (4) high lateral track resistance allowing higher speeds in combination with tilting technology, (5) great precision of track-geometry parameters by application of precise concrete sleepers, and (6) elimination of churning of ballast particles at higher speeds. However as explained by Esveld (2001), in comparison to the ballasted track the disadvantages of the slab track are generally: (a) higher construction costs, (b) large alterations in track position and superelevation can only be made possible by substantial amounts of work, (c) adaptability to larger displacements in the embankment is relatively small and (d) in case of derailment, repair works will take much more time and effort.

Results from a general cost evaluations conducted by Schilder and Diederich (2007) to economically compare ballasted tracks and slab tracks are shown in Figure 6. It can be seen that slab track is more efficient in a long-term perspective. However the promise of employing slab tracks being maintenance free for a long term depends on several factors. The most important issue would be the type of slab track, which is the best for particular circumstances.

Different slab track systems developed around the world. They have been explained in detail in Michas (2012). These systems can generally be divided into two main categories:

(1) Discrete rail support systems
- o with sleepers or blocks encased in concrete (e.g. Rheda 2000 system)
- o sleepers on top of asphalt-concrete roadbed
- o prefabricated concrete slabs (e.g. Shinkansen system)
- o monolithic designs

(2) Continuous rail support systems
- o embedded rail structure (ERS)
- o clamped and continuously supported rail (e.g. Cocon track system)

In order to reduce the high construction costs of high-speed rails, a new installation concept, called Rheda System, was developed by Rail-One company in Germany in 2000 (Esveld, 2003). Chief characteristics of the supporting concrete slab in this design include modified twin block sleepers with a lattice truss. By omitting the concrete trough, a complete step in the construction work sequence was eliminated. One of the main features of a slab track is the type of fastening which is applied to mitigate the transfer of noise from the train to the super structure.

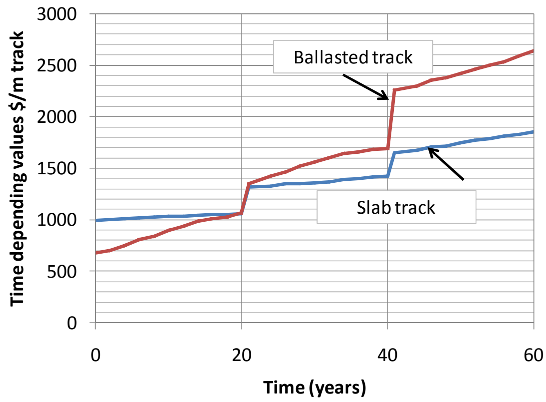

Figure 6 Time depending cost of ballasted track and slab track (data taken from Schilder and Diederich, 2007)

There are a number of methods of fastening the rail to the slab and they have different vibration mitigation characteristics. Within the different slab track types, floating slab tracks provide an effective way to reduce vibration transmission from railway traffic to the ground (Lombaert et al., 2006). The floating slab track (FST) is a method of separating the slab track and the superstructure. This can be carried out using elastomers or springs. The amount of elastomer used can vary from fully supported to linear and point (discrete) supports. Separation can also be achieved by use of a large spring, which absorbs the noise and vibration. Some products allow their stiffness and height to be adjusted post construction. By adding an elastic layer beneath the slab, the natural frequency of the system is reduced, at the expense of increasing its cost.

Ballast-less tracks have already been applied to achieve high speed rail systems. Although slab track offers many benefits, its performance depends on careful design and construction methodologies. The main shortcoming of the slab track is its higher installation cost. Apart from that, railway administrations and design engineers often prefer to use traditional ballasted track designs instead of modern slab track designs, because extensive experience has been collected with the use of the former track type. Accordingly, it is suggested to use slab tracks in combination with ballasted tracks, with stabilised formation and inclusion of proper geosynthetics. However, slab tracks are strongly recommended for HSR bridges and tunnels to minimise the maintenance time and costs.

5. CONCLUSIONS

High speed rail systems have been one of the most innovative elements affecting passenger transport since the Second World War; and Japan was effectively the birthplace of the high speed rail (HSR). It is clear that, high speed railways are expensive to construct, represent a considerable spending in the transport infrastructure, and produce economic and social effects. The factors that must be considered when implementing a high speed rail system can be complex and do not always work in favour of the nation building the rail line. Sometimes these factors such as the economic conditions of a nation or the natural geography cannot be directly controlled.

Some benefits of implementation of HSR can be summarised as follows: (1) reduction in carbon emissions, (2) increasing travel punctuality and safety for interstate commuters, (3) offering more comfort than airlines due to larger seats for the same ticket prices, more doors for exit and entrance, quieter cabins and no strict luggage weight restrictions, (4) contributing in development of regional areas and improving the land value along the demand corridors due to increased accessibility, (5) increasing desirability of Australia as a tourist destination, and as a host for world major events, (6) reducing air pollution, vehicle accidents and traffic congestion, and (7) providing services to/from Sydney, while the Sydney Airport curfew is on after midnight.

Two major issues connected to high speed train operations including critical velocity and transition problems have been discussed and various methods to avoid the train vibration at higher speeds are explained. It has been expressed that geosynthetics can provide an important option to improve track support stabilisation and thereby reduce the track maintenance costs and operation costs. In railroad construction, geosynthetics may be installed within or beneath the ballast or subballast layers.

The effectiveness of semi-rigid inclusion ground improvement techniques, particularly stone columns was numerically investigated for HSR systems in controlling the settlement of weak formations. The applied numerical study assessed the relationship between the column position in the track cross section and the overall settlement of the ballasted rail formation. The numerical results showed that the overall settlement of the track reduces significantly with the use of columns close to the centre of the track and not just under the rail. In addition, application of one layer of geogrids between sub-ballast and sub-grade assists to reduce the maximum settlement of track decreasing the future maintenance costs.

The advantages of using slab tracks, also called ballast-less tracks, consist of rails fastened to continuous reinforced concrete slabs with free cracking, have been explained. In comparison to ballasted tracks, slab tracks reduce the construction height; reduce track maintenance like tamping; aligning and cleaning of tracks in stations; reduce the wear down of rail; provide better riding comfort at high speeds; provide higher availability, reduce vibration and secondary airborne noises; improve load distribution, thus reduce dynamic stresses on subsoil; provide high lateral and longitudinal track stability (reduce risk of track buckling) and eliminate problems with vegetation control, which is essential for a ballasted structure. On the other hand, the substantial higher cost of slab track construction makes the rail organisations to choose a combined system using slab tracks mostly for stations, tunnels, bridges and viaducts, while using stabilised ballasted tracks for the main corridors. As a final point, high speed rail transport might not necessarily be one the best solutions for the transportation at present in Australia, but it can be what a nation needs to succeed in its future transportation system.

6. REFERENCES

AECOM (2013), "High speed rail study phase 2" Report prepared for the Department of Infrastructure and Transport by AECOM Australia Pty Ltd with association with GRIMSHAW, KPMG, SKM, ACIL Tasman, Booz & Co and Hyder, http:// www.infrastructure.gov.au/rail/trains/ high_speed/files (Accessed on 14 April 2013).

AECOM (2011), "High speed rail study phase 1" Report by AECOM Australia, GRIMSHAW, KPMG and SKM. http://www.infrastructure.gov.au/rail/trains/high_speed/files /HSR_Phase1_Report.pdf. (Accessed on 8 July 2012).

Arup-TMG (2001), "East coast very high speed train scoping study", (http://www.infrastructure.gov.au /rail/trains/high_speed (Accessed on 1 April 2013).

Canberra Business Council (2008). "High speed rail for Australia: An opportunity for the 21st Century", (http://www.canberrabusinesscouncil. com.au/submissions /files (Accessed on 1 July 2012).

Department of Infrastructure and Transport, Australian Government, (2012), "High speed rail study: Moving forward with high speed rail." http://www.infrastructure.gov.au/rail/trains/ high_speed/index.aspx (Accessed on 1 April 2013).

Esveld, C. (2003), "Recent developments in slab track", European Railway Review, 23 May 2003, pp81-85.

Esveld, C. (2001) "Modern railway track". MRT-Productions, Zaltbommel. ISBN 90-800324-3-3 (www.esveld.com).

Fatahi, B., Basack, S., Premananda, S. and Khabbaz, H. 2012, 'Settlement prediction and back analysis of Young's modulus and dilation angle of stone columns', Australian Journal of Civil Engineering, Vol. 10(1), pp67-78.

Fatahi, B., Khabbaz, H. and Indraratna, B. (2009), "Parametric studies on bioengineering effects of tree root-based suction on ground behaviour", Ecological Engineering, Vol. 35(10), pp1415-1426.

Fatahi, B. and Khabbaz, H. (2011). "Enhancement of ballasted rail track performance using geosynthetics", Proceedings of the Geo-Hunan International Conference, ed Adam F. Sevi; Jiuyuan Liu; Cheng-wei Chen; Sao-Jeng Chao, ASCE, USA, pp222-230.

Fatahi, B., Khabbaz, H. and Ho, L.H. (2011), "Effects of geotextiles on drainage performance of ballasted rail tracks", Australian Geomechanics Journal, Vol. 46(4), pp91-102.

Fatahi, B., Khabbaz, H. and Indraratna, B. (2008), "Analysis of matric suction effects induced by tree roots on rail track subgrade", Conference on Railway Engineering, Perth, WA, in Proceedings of CORE2008 Conference on Railway Engineering, RTSA, Australia, pp. 599-610.

Galvin, P., Romero, A. and Dominguez, J. (2010). "Fully three-dimensional analysis of high-speed train-track-soil-structure dynamic interaction". Journal of Sound and Vibration Vol. 329(24), pp5147-5163.

Givoni, M. (2006), "Development and impact of the modern high-speed rail", Transport Reviews.

Gourvish, T. (2010), "The high speed rail revolution: history and prospects", Report of High Speed 2, London www.railwaysarchive.co.uk/documents/HS2_TheHighSpeed RailRevolutionHistoryAndProspects2010.pdf (Accessed on 7 July 2012).

Indraratna B. and Khabbaz, H. (2008). "Geotechnical aspects of ballasted rail tracks and stabilising underlying soft soil formation". Proceedings of the International Conference on Advances in Transportation Geotechnics, Edited by Ellis et al., University of Nottingham, UK, pp593-599.

Indraratna, B., Khabbaz, H., Salim, W. and Christie, D. (2006), "Geotechnical properties of ballast and the role of geosynthetics", Journal of Ground Improvement, ISSMGE, Vol. 10 (3), pp91-101.

Indraratna B., Nimbalkar S. and Rujikiatkamjorn C. (2012) "Track stabilisation with geosynthetics and geodrains, and performance verification through field monitoring and numerical modeling", International Journal of Railway Technology, Vol. 1(1), pp195-219.

Indraratna, B., Shahin, M.A. and Salim, W. (2007), "Stabilisation of granular media and formation soil using geosynthetics with special reference to railway engineering", J. Ground Improvement, Vol. 11(1), pp27-43.

Indraratna, B., Salim, W. and Rujikiatkamjorn, C. (2011), Advanced rail geotechnology - ballasted track, Taylor & Francis Group Publisher, United Kingdom.

Lombaert, G., Degrande, G., Vanhauwere, B., Vandeborght, B. and François, S. (2006), "The control of ground-borne vibrations from railway traffic by means of continuous floating slabs". Journal of Sound Vibration, Vol. 297, Issue 3-5, pp946-961.

Lieberenz, K. and Weisemann, U. (2002), "Geosynthetics in dynamically stressed earth structures of railway lines", Rail International, Schienen der Welt. Vol. 33, pp30-39.

Madshus, C., Lacasse, S., Kaynia, A. and Harvik, L. (2004), "Geodynamic challenges in high speed railways projects". ASCE Proc. Geotechnical Engineering for Transportation Projects , GSP 126.

Michas, G.(2012), "Slab track systems for high-speed railways", Master Degree Project, School of Architecture and the Built Environment, Royal Institute of Technology, Stockholm, Sweden, p95.

Okada, H. (2007), "High-speed railways in Asia: high-speed railways in China", Japan Railway and Transport Review, No. 48, pp22-29.

Perry, J. (2010), "Strategic directions for Australian rail", Rail Express Issue1, June 2010, pp4-6.

PLAXIS (2008), "User Manual of PLAXIS 2D", Version 9, Delft, The Netherlands.

Raymond G.P. (1994), "Durability of geotextiles in railway rehabilitation", Transportation Research Record, Washington, DC USA, Issue 1439, pp12-19.

Rose, J. and Lees, H. (2008), "Long-term assessment of asphalt trackbed component materials' Properties and Performance", Proceedings of AREMA 2008 Annual Conference, Salt Lake City, UT, 28p.

Schilder R. and Diederich, D. (2007), "Installation Quality of Slab Track - A Decisive Factor for Maintenance". RTR Special. Austria, July, pp76-78.

Selig, E. T. and Waters, J.M., (1994), Track geotechnology and substructure management, Thomas Telford Services, London, UK, Reprint 2007.

William, J. (2008), "Rail Race: Maglev or HSR, what is the future?", The Rail Debate and Shape History, Engineer News Record. http://www.canvmaglev.com/pid5newsmedia/news/2009-07-21 ENR (Accessed on 8 April 2013).

Woodward, P., Kacimi, A., Laghrouche, O. and Medero G. (2012), "Modelling the effects of ground and ballast stabilisation and reinforcement technologies on the dynamic performance of high speed ballasted railways", Proc. ICGI 2012, eds. Indraratna et al., 30 Oct.-2 Nov., Wollongong, Australia, pp945-950.

Wright, M (2009), "Fly by rail – zero emissions transport capital to capital", Beyond Zero Emissions Campaign. http://beyondzeroemissions.org/node/64 (Accessed on 4 July 2012).

Yang, Y.B., Hung, H.H. and Chang, D.W. (2003), "Train-induced wave propagation in layered soils using finite and infinite element simulation". Soil Dynamics and Earthquake Engineering, Vol. 23(4), pp263-278.