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Numerical Modelling of Geotextile Reinforcement of Ballasted Railway under High Speed Train

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Abstract: In recent years, it has become evident that high speed trains can cause severe track-settlement problems along certain sections of high speed train lines. The dynamic loading that occurs during the passage of high-speed trains leads to degradation of the ballast and underlying layers. We used LS-DYNA Software to analyze the impact of high-speed train load on a reinforced ballasted rail line, using non-reinforced ballasted rail line as a control. LS-DYNA is powerful finite element software that enables the modeling of parameters including static and dynamic load, traffic line, contacts, boundary conditions, materials and element types. The velocity of the train was defined as PRESCRIBED MOTION, the static load was defined as LONDE_NODE SET and the traffic line was defined as RAIL_TRACK and RAIL_TRAIN. The contacts between parts, segments and nodes of the high-speed ballasted rail track were ssdefined as CONTACT SINGLE SURFACE, CONTACT SURFACE_SURFACE and CONTACT FORCED TRANDUCER PENALTY, respectively. The result show that the deformation rate for reinforced ballasted rail track is 24% less than that for the non-reinforced ballasted track. Furthermore, the stress state of the reinforced ballasted track is <70% that for the non-reinforced ballasted track. Similarly, the strain state of the reinforced ballasted track containing geotextile between the sub-ballast and the subgrade is <76% that of the non-reinforced ballasted track. The results indicate that geotextile reinforcement can be used to strengthen weak, soft subgrade ballasted railway tracks.

Key words: Geotextile, reinforcement, subgrade, train load, dynamic impact

INTRODUCTION

Geotextiles are among the first textile products in recorded human history. Excavations of ancient Egyptian sites have shown that mats of grass and linen were used in road construction to stabilize the roads and their edges. These early geotextiles were made of natural fibers, fabrics or vegetation that was mixed with soil to improve road quality, particularly for roads made on unstable ground (Agrawl, 2011; Meena and Dey, 2013). Geotextiles are now highly developed products that must comply with numerous standards. They perform stabilization functions by providing a dense mass of fibers at the interface between two layers. Geotextiles have been shown to be among the most versatile and cost-effective ground modification materials and their use has expanded rapidly into most areas of civil, geotechnical, environmental, coastal and hydraulic engineering (Agrawl, 2011; Berg *et al*., 2000). They form the major component of the field of geosynthetics, the others being geogrids, geomembranes and geocomposites. ASTM defined geotextiles as permeable textile materials used in contact with soil, rock, earth or any other geotechnical-related material as an integral part of civil engineering projects, structures or systems.

Geotextiles are permeable textile structures made of polymeric materials. They are used for reinforcement, stabilization, separation and filtration purposes. The polymers are formed into geotextiles using either woven or non-woven methods with each type having unique applications and benefits (Burd and Brocklehurst, 1990; Carotti and Rimoldi, 1998). In general, woven geotextiles exhibit high tensile strength and little elongation capacity while non-woven geotextiles usually have lower tensile strength and greater elongation and flow rate capacities. As a continuous sheet, geotextiles can also function as separators in addition to reinforcement, preventing intermixing of the aggregate base and subgrade materials. Geotextiles can be used in pavement as a stiff material that maintains the full thickness and integrity on soft subgrade throughout its service life (Chen *et al*., 2007; Dondi, 1994). Non-woven geotextiles are generally used for separation and filtration while high strength woven geotextiles are used for both base reinforcement and subgrade stabilization.

Railway embankments built on soft soil require appropriate ground improvement and soil compaction. A railway line can be considered a multilayered composite system composed of natural ground, a soil-fill reinforcement layer, the rail track system and the train

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wheel loads (DOT, 2007; Gullu, 2013). Soft subgrade soil has poor engineering performance properties because of its clay, silt-clay and silt content. Past research has shown that a soft layer of soil is commonly placed on top of the subgrade and directly below the aggregate base (Hopking *et al*., 2006). This is of great engineering significance in the design and performance of high-speed railways. The purpose of the track is to convert the wheel load to relatively uniform stress on the subgrade. The track substructure layer (ballast, sub-ballast and subgrade) has enormous influence on the performance of the railway. All stresses and thus settlement, occur in this layer and settlement resulting from static and dynamic loading can be short or long-term. Geosynthetic materials have proven to be suitable as reinforcement for soft subgrade soil. They promote improved soil quality and thus increase the structural stability of the subgrade. The role of geosynthetic materials is to increase the soil shear strength in the railway substructure by providing a bonding mechanism in the geosynthetic soil system (Giroud and Bonaparte, 1985).

The application of a vertical load causes lateral forces that tend to spread the aggregate particles laterally which leads to local deformation of the fill. Aggregate particles are restrained from moving laterally at the interface of a geosynthetic layer (mainly geogrids) and the base, because of frictional interactions and interlocking between the granular base and the geosynthetic material (Aknod, 2012). Geosynthetic reinforcement can also absorb additional shear stresses between the subgrade and the base which would otherwise be applied to the soft subgrade. This improves the load distribution on top of the subgrade layer and reduces the base thickness required. Several studies have reported that the inclusion of reinforcement resulted in an increase in the ultimate bearing capacity of reinforced geomaterial (Berg *et al*., 2000; Chen *et al*., 2007). The improved bearing capacity is achieved by shifting the failure envelope of the pavement system from a relatively weak subgrade to a relatively stiff base layer. As a result, the bearing failure model for subgrade may change from punching failure without reinforcement to general failure with ideal reinforcement (Zomberg, 1987).

The structural stability of soil is greatly improved by the tensile strength of geosynthetic material, similarly to the reinforcement of concrete with steel, i.e., concrete is weak in tension, so steel is used to strengthen it. Geosynthetic materials function in a similar manner as the reinforcing steel by providing strength that helps to hold the soil in place (Agrawl, 2011).

The finite element method has sufficient capacity to solve a variety of geotechnical engineering problems, including analysis of the performance of geotextile layers in railway construction and it can accommodate subgrades ranging from very silty to soft clayey (Hopking *et al*., 2006). In such situations the geotextile functions as a reinforcement layer to control settlement and to increase the bearing capacity. In recent decades the application of numerical methods has expanded in all aspects of engineering and increasingly powerful software is being used to address various geotechnical problems.

Problem statement: The dynamic loading of high-speed trains causes track settlement and leads to the degradation of the ballast and underlying layers. The settlement results from permanent deformation of the ballast and underlying soil. The extent of settlement depends on the quality and behavior of the ballast, the sub-ballast and the subgrade. As soon as the track geometry begins to degrade, variations in the dynamic train/track interaction forces increase and this accelerates the track deterioration process. Stabilization of railway foundations built on soft to very soft clayey subgrades is of major importance in high-speed railway construction and their safe operation (Hallquist, 2006). Amongst the variety of soft soil stabilization methods for railway foundation construction in the majority of cases the use of geotextile materials is appropriate and enables economical design. The selection of suitable geotextile materials for railway foundation stabilization is based on precise evaluation of the tensile force which can be assessed using various closed form or numerical solutions.

Geotextiles generally assure an effective service life for a granular soil layer constructed directly on a soft foundation soil. In many applications (e.g., railways, highways, access roads, car parks) where a granular layer is constructed directly on a soft subgrade, under the traffic loadings that occur the granular layer commonly loses bearing capacity because of intermixing of the granular material with the soft subgrade.

In this study, we investigated the reinforcement of railway foundations using geotextile material to mitigate the effects of high dynamic loading on soft subgrade soil. The main research objective was to evaluate the reinforcement by geotextile materials used to accommodate the dynamic loading effects of high-speed trains on soft subgrade soil. The finite element method was chosen as the most suitable numerical method because it enabled accurate simulation of the interaction between the ballasted material and the subgrade with the chosen geotextile material. It also enabled a three-dimensional model of the complex stress and strain states and calculation of the deformation of the railway track caused by the load of the moving train.

The finite element method is one of the most powerful and general approaches for structural analysis, principally because of its versatility. The method can be applied to various physical systems, the problems analyzed can have arbitrary shape, load and support conditions and various combinations of types, shapes and physical properties can be simulated. Such numerical procedures are typically used when the problem to be addressed is too complicated to be solved satisfactorily using classical analytical methods. Many software programs have been developed for the analysis of structures using this method but the program LS-DYNA is one of the most powerful available. The explicit finite element code has proven to be an effective tool, especially for transient and impact load analysis. In this study, the finite element analysis was conducted using LS-DYNA (Milligan and Love, 1984).

Background and literature review: Gullu (2013) presented a numerical study involving a geotextile stabilized highway embankment under vibration loading. The effects of 1-3 layers of geotextile placed at various locations within the embankment were analyzed and the displacement and safety factors were assessed. The embankment comprised compacted fill placed over soft soil. The numerical analysis involved the finite element method, applied in two dimensions using PLAXIS. The results indicated that one layer of geotextile placed on soft soil provided good displacement and there was an adequate safety factor with two and three layers. From an economic perspective, single and double geotextile layers are appropriate for highway embankments with respect to vibration.

Burd and Brocklehurst (1990) performed a finite element investigation of the use of geosynthetic materials for the reinforcement of unpaved roads. They performed a plane strain analysis with a static load and quantified the effect of reinforcement stiffness on deflection. It was assumed that no slip occurred at the soil-geosynthetic material interface. An elastic perfectly plastic frictionless material model was used for the clay subgrade layer, an elastic perfectly plastic frictional model with non-associative flow rule for the base and the reinforcement was modeled as an elastic material that could not sustain compression. The results indicated that the stiffness of the reinforcement had a marginal effect on the resulting deflection; however it had a substantial effect on the magnitude of the shear stress acting at the soil-geosynthetic material interface. It was clear that the geosynthetic stiffness had a large effect on the shear stress at the interface with the high-stiffness geosynthetic material creating the highest shear stress. The researchers suggested that this was a result of the geosynthetic material providing lateral restraint on the base material. They also concluded that there was little benefit from using an excessively stiff geosynthetic material for small deflections under static loading as large shear stresses are developed at the soil-base interface.

Dondi (1994) studied a geosynthetic-reinforced paved road. Various material models were used for each layer of the road's cross-section. An elastic material model was used for both the hot mixture of asphalt material and the geosynthetic material. The base material was assumed to be an elastic perfectly plastic, cohesive, non-associative material using the Drucker-Prager failure criterion. The subgrade was assumed to be an elastic perfectly plastic, cohesive Cam-clay type material. In addition, the frictional behavior of the geosynthetic-soil interface was assumed to follow a Mohr-Coulomb elasto plastic model. The results showed that the use of geosynthetic materials in paved roads is beneficial. For instance, under Italian design loading (130 kN axle load) there was a 20% reduction in vertical deflection calculated for a geosynthetic modulus of 1200 kN m^{-1} and a 15% reduction for a modulus of 600 kN m^{-1} and it was found that the shear stresses in the subgrade were reduced in the reinforced sections.

Geogrids are used in flexible pavements in two major applications: base reinforcement and subgrade stabilization. In base reinforcement applications the geogrid is placed within or at the bottom of unbound layers of a flexible pavement system and it improves the load-carrying capacity of the pavement under repeated traffic. In subgrade stabilization applications a geogrid is used to build a construction platform over weak subgrades, enabling the carriage of equipment and facilitating construction of the pavement system without excessive deformation of the subgrade (Giroud and Bonaparte, 1985).

Geogrids are designed to carry the shear stresses caused by vehicle loads at the interface between the base course and the subgrade soil (Milligan and Love, 1984). Interlocking between the geogrid and the base course aggregate results in reduced lateral movement of the aggregate and the outward shear stresses are transmitted to the subgrade. At the bottom surface of the base course, protrusion of the confined aggregate through the geogrid provides a rough surface that resists lateral movement of the subgrade and increases the subgrade bearing capacity.

Geogrids show an elastic-plastic material behavior, so they react quickly to applied loads. Creep phenomena do not occur in the case of short-term impact loading and hence the entire tensile resistance of the geogrid can be mobilized. Furthermore, geogrids enable an increase in the dynamic dumping characteristics of the reinforced soil compared with non-reinforced soil, through the energy that is directly absorbed by the geogrid and as a result of friction generated in the dynamic stage (Carotti and Rimoldi, 1998).

Giroud and Bonaparte (1985) showed that geogrids can improve the performance of subgrade soil through three mechanisms confinement; improved load distribution through the base layer and a tensioned membrane effect which reduces stresses. For pavements constructed on soft subgrades, the reinforcement should be placed at or near the bottom of the base.

Wathugala used the ABAQUS finite element program to investigate the decrease in rut depth as a result of placing a geogrid membrane at the base-subgrade interface in a flexible pavement system. A series of finite element simulations was carried out to evaluate the benefits of integrating a high modulus geogrid into the pavement foundation. Three placements of the geogrid were studied at the asphalt-concrete interface; at the base-subgrade interface and inside the base layer at 1/3 of its thickness, measured from the bottom. It was found that placement of the geogrid reinforcement at the base-asphalt concrete interface provided the greatest reduction (46-48%) in fatigue strain.

Gaps in existing research: The literature search revealed no sufficiently in-depth report of the dynamic responses of geotextile reinforced ballasted railway track, specifically studied using the LS-DYNA finite element computer code which is capable of modeling real-world dynamic forces. Most previous studies focused on finite element simulations of static loads of pavement road and did not sufficiently address dynamic effects.

MATERIALS AND METHODS

Geotextiles are widely used in engineering to reinforce structures and improve the material tensile strength. Various methods have been applied to calculate the contribution of geotextile materials in railway and road structures. Finite element analysis is one of the most commonly used methods for undertaking engineering calculations. LS-DYNA is powerful finite element software used in engineering applications. It was applied in this study to analyze the dynamic impact of a high-speed train on geotextile-reinforced subgrade ballasted railway track and was used to model various parameters including the geometry, element type, material, static and dynamic characteristics, contact forces and track line.

Material model: Geotextiles are typically made from petroleum products including polypropylene, polyester and polyethylene but can also be made from fiberglass. Geotextiles may be further characterized by the manner in which they are manufactured. For instance, woven geotextiles are made by weaving individual filaments together to create an interlocking structure. Conversely, non-woven geotextiles are manufactured by bonding together randomly oriented short fibers or filaments to form a planar structure. For non-woven geotextiles the bonding process can be chemical, thermal or mechanical. Chemical bonds involve the use of a glue to hold the fibers together, thermal bonding is achieved by melting the fibers together and needle punching creates mechanical bonds. Many studies have reported the use of LS-DYNA in material models and in this study we defined and investigated various materials using this software. In this study the rail was modeled as plastic kinematic and the sleepers as elastic material. The ballast and sub-ballast were modeled as rectangular prisms of linearly elastic material bounded by non-rotatable and non-movable side and bottom boundaries. The soft subgrade soil was considered to be a rectangular prism bounded by non movable side and bottom boundaries and modeled as linearly visco-elastic materials. The train was modeled as a rigid body as it is not able to be deformed. The geotextile was modeled as plastic kinematic material. Table 1 lists the material properties of each component.

Geometry: LS-DYNA comprises a wide range of geometries for modeling various components of the high-speed railway and an element menu. Beam elements have been used in rail and sleeper modeling. A beam element is an element involving assumptions that reduce the problem mathematically to a single dimension. The primary solution variable is then a function of the length direction of the beam. For this solution to be valid, the length of the element must be large compared with its

Table 1: Material properties of each component high speed railway model

Components	L (mm)	W (mm)	D (mm)	Density (gm/mm^3)	Young modulu (MPa)	Poison ratio
Rail	30000	65000	170	7850	2×10^5	0.250
Sleeper	25250	25000	243	24×10^{-3}	70	0.300
Ballast	30000	10000	350	16×10^{-4}	150	0.350
sub ballast	30000	10000	150	19×10^{-3}	80	0.350
Geotextile	30000	10000	2	75	42	0.400
Subgrade	30000	10000	5500	20×10^{-3}	10	0.400
Train (rigid)	45000	15000	2000	7.67×10^{-5}	2.1×10^5	0.250

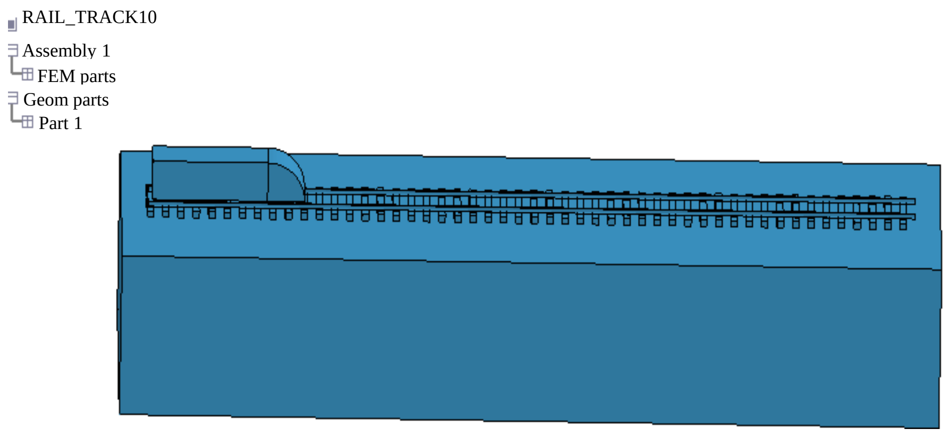

Fig. 1: The high-speed train on a ballasted railway

cross-section. There are two main types of beam element formulation: the Euler-Bernoulli theory and the Timoshenko theory. The Euler-Bernoulli theory assumes that the plan cross-sections are initially normal to the beam axis and remain plane and undistorted. In LS-DYNA, all beam elements used in linear or quadratic interpolation are based on this theory. The Timoshenko beam theory allows the elements to have transverse shear strain, so that the cross-sections do not have to remain normal to the beam axis. In this study, solid elements were used to model the ballast, sub-ballast and subgrade. Solid elements in two and three dimensions are available in the finite element model. The two-dimension solid element enables modeling of plane and axisymmetrical problems. In three dimensions, the isoperimetric hexahedron element is the most common but in some cases a complex geometry may require tetrahedron elements but these are generally only recommended for filling awkward parts of the mesh. There are many shell elements in finite element modeling, each of which is placed in one of three categories: general purpose shells, thin shells and thick shells. General purpose shells are capable of deformation resulting from transverse shear stress. Thin shells should only be used if transverse shear deformation is negligible; in this case, the elements satisfy the Kirchhoff assumption throughout the analysis. Thick shells take transverse shear deformation into account and should be used when this deformation is important in the model. Geotextile materials were modeled as a shell element in the present study as the thickness is much smaller than the other dimensions. The train was modeled as a rigid body. A rigid part represents a part of the model that is so much stiffer than the other components that its deformation can be considered negligible. Figure 1 shows the high-speed train on a ballasted railway.

Boundary conditions: Modeling of boundary conditions is often the most critical factor in achieving accurate and reliable data from a finite element analysis (LSTC, 2014). To ensure a good representation of the physical conditions, several tools are used to provide appropriate boundary conditions such as fixing the ends to be unmovable. The load application is another important type of boundary set. The dynamic load on the track component was modeled using the prescribed motion rigid finite element LS-DYNA code and the dead load component of the train-rail contact was modeled as an axial load node set command. Details of the prescribed motion and dead axial load protocol are discussed below. For both the dynamic and static loads, the displacement direction and rotation were constrained in their respective axes.

The static train load was applied to the wheel-rail contact. Each axel comprised two wheel sets (an axle with two wheels). The total load on both axles was equivalent

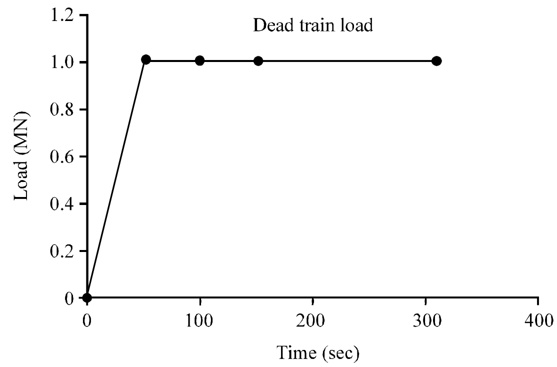

Fig. 2: Train load

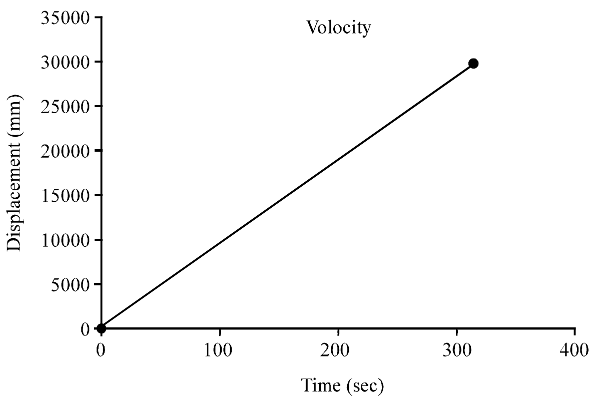

Fig. 3: Train velocity

to 320 tons, distributed equally at the four wheels (i.e., 80 tons per wheel). The load was defined and prescribed in LS-DYNA as the LOAD_NODE SET command. Figure 2 shows the distributed train load with respect to time. The dynamic load was described in the LS-DYNA Software program as the BOUNDARY_PRESCRIBED_MOTION command. The finite element model in LS-DYNA defined the movement of the train in terms of the displacement versus time graph. The maximum permissible axle load of 160 kN was taken into account during the entire modeling processes. The simulation was conducted based on a speed of 350 kN m^{-1}. The axle spacing, bogie wheelbase and train speed corresponded to the dimensions of the ballasted railway track finite element model, particularly the sleeper spacing (0.6 m). This approach ensured that each wheel set was located exactly above a sleeper for the period of time considered. Figure 3 shows the train velocity in terms of displacement relative to time.

RAIL_TRACK and RAIL_TRAIN: The vehicle-rail and rail-track contacts are important in simulating a ballasted railway using LS-DYNA finite element code. This is the only software able to define the railway track line to provide an accurate simulated model of the rail-track interaction using the RAIL_TRACK and RAIL_TRAIN LS-DYNA commands.

Contact algorithms: The contact algorithm which is unique to LS-DYNA, models the contact between parts, segments and nodes. It is defined and for the first time applied here to ballasted railway track. This contact algorithm was defined by the commands CONTACT_AUTOMATIC_SINGLE SURFACE, CONTACT SURFACE-SURFACE and CONTACT FORCED TRANDUCER PENALTY which were applicable to modeling the contacts between the rail, sleeper, ballast, sub-ballast and subgrade. The algorithm used a penalty method to model the contact interfaces of the various track components.

Soft subgrade ballasted railway track deformation: In general, implicit methods have the form:

$$U^{n+1} = f(\ddot{u}^{n+1}, \dot{u}^{n+1}, u^{n}, ...) \quad (1)$$

Computation of the current nodal displacements requires knowledge of the time derivatives. Consequently, simultaneous equations need to be solved to compute the current displacements. Explicit methods have the form:

$$U^{n+1} = f(u^{n}, \dot{u}^{n}, \ddot{u}^{n}, u^{n+1}, ...) \quad (2)$$

Therefore, the current nodal displacements can be determined in terms of completely historical information, consisting of displacements and time derivatives of displacements at previous time steps.

Stress-strain state of ballasted railway track: Stress and plastic strain contours based on finite element analysis are presented. The results provide information about the behavior of the ballasted railway track and foundations with respect to the stress-strain state under the dynamic train-track interactions.

Sliding energy: The sliding energy measures the penetration of parts, elements and nodes into other components where the output shows positive values.

RESULTS AND DISCUSSION

The model results for the finite element analysis of a high-speed train on reinforced subgrade ballasted railway track were calculated and are presented here. The

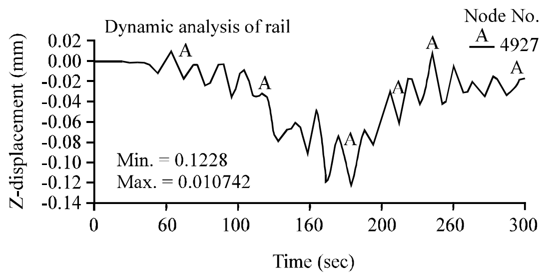

Fig. 4: Deformation of reinforced ballasted track for a train speed of 350 km h^{-1}

simulations provide new information regarding the global and local dynamic response of ballasted railway track to high-speed train load.

Analysis of geotextile-reinforced ballasted railway: The axisymmetrical finite element simulations using LS-DYNA Software were carried out to evaluate the benefits of using geotextiles in high-speed railway track construction. The results describe the behavior of soft subgrade soil reinforced with geotextile materials under axisymmetric and dynamic loading conditions. The results of geotextile reinforcement of soft subgrade soil improvement using geotextile are presented.

Analysis of geotextile-reinforced ballasted railway deformation: Figure 4 shows the average deformation of reinforced soft subgrade soil under repeated dynamic load for a train speed of 350 km h^{-1} (determined from the mean of measurements of displacement plotted against travel time). The substructure layers exhibited an increase in average vertical deformation. Thus, the use of geotextile was essential in ensuring a reduction in lateral spread of the ballast and vertical deformation. The confining and reinforcing properties of the geotextile improved the lateral stability of the ballast. This has a significant bearing on the maintenance of rail tracks. Reducing the lateral movement of ballast decreases the need for additional layers of crib and shoulder ballast during maintenance. If a greater internal confining pressure in the track can be provided by inclusion of a geotextile layer within the ballast bed, then the lateral deformation of the ballast will be substantially decreased. The track substructure is essentially self-supporting with minimal lateral restraints. The effective confining pressure is a key parameter governing the design of railway tracks with implications for ballast movement and associated track maintenance Thus, an increase in track confinement through the use of geotextiles is a significant factor in maintenance, along with other factors including reduced tamping, leveling and lining. Soft subgrade ballasted railway track containing geotextiles showed the smallest deformation. This is because of the highly frictional angular particles of fresh ballast which develops increased apparent friction with the geotextile layer.

Analysis of the stress-strain state of geotextile reinforced ballasted railway: Geotextile materials have very good interlocking and frictional capabilities which provide tensile resistance to any further lateral movement; therefore, they improve the strength of ballasted railway track on soft subgrade soil. They improve the bearing capacity of the soft subgrade soil by forcing the potential bearing capacity failure surface to move to an alternate higher-strength path. The tensile stress that develops in the geotextile is a result of the development of ruts or deformation in the soft subgrade soil which leads to the formation of a membrane-type support. As the geotextile used in the numerical modeling has a high tensile modulus, the tensile stresses that developed in the geotextile membrane and the vertical component of the membrane stress enabled the weak soil to support the stress applied as a result of loading. The improved strength of the soft subgrade material resulting from inclusion of a geotextile material depends on the soil characteristics and the value of the subgrade soil. In terms of improved strength, geotextiles provide greater benefits to soft subgrade soils than to good subgrade soil. Geotextile reinforcement leads to a decrease in surface penetration and deformation and hence to improved distribution of stress in soils and enhanced resistance of the soil to dynamic loading. Figure 5 shows the stress strain state of reinforced ballasted railway.

Analysis of non-reinforced ballasted railway deformation: The total deformation of the ballasted railway track along successive sleepers resulting from a dynamic train load was calculated using LS-DYNA. Figure 6 shows the deformation for a non-reinforced ballasted railway.

Analysis of stress-strain in a ballasted railway track without geotextile: Stress is a basic component of ballasted railway track analysis. The stress-strain output indicates the capacity of the materials modulus and the design quality and safety. If the materials are sufficient to withstand the stresses from the dynamic and train loads, the deterioration and settlement problems are mitigated along each component of the structures. The maximum compressive stress value of the railway track may also be critical if the vehicles impose high dynamic forces between the wheel flanges and the railhead. Having calculated the magnitude of the compressive stress, comparisons should be made between the stress and the

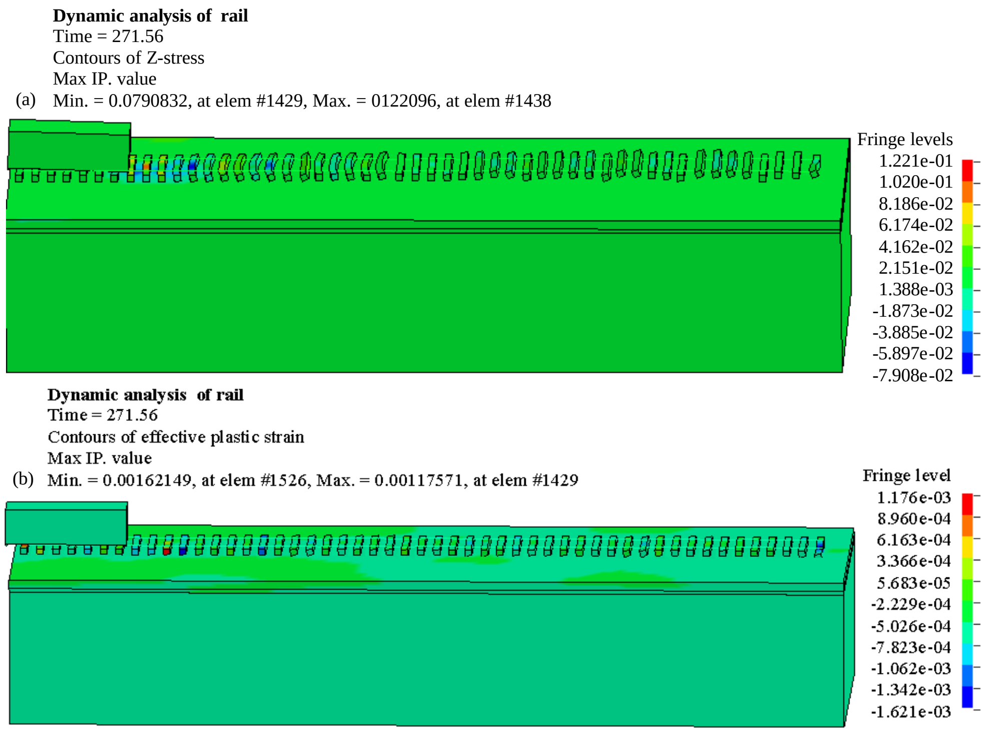

Fig. 5: a) stress in reinforced ballasted railway for a train speed of 350 km h^{-1} and b) plastic strain in reinforced ballasted railway for a train speed of 350 km h^{-1}

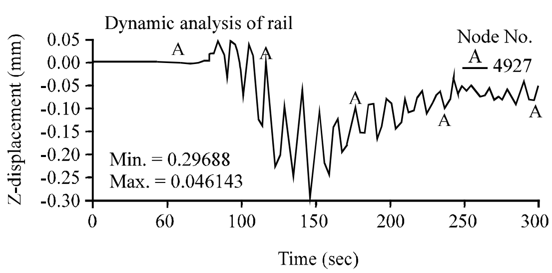

Fig. 6: Deformation a non-reinforced ballasted railway for a train speed of 350 km h^{-1}

allowable limit. Stress components for ballasted railway track are calculated and compared with the materials modulus. This enables assessment of how much the dynamic impact contributes to deterioration of the ballasted railway track under repeated loading. Figure 7 shows the stress-strain for a non-reinforced ballasted railway.

For a train travelling at 350 km h^{-1} on reinforced ballasted railway the maximum deformation dynamic load was 0.1228 mm and on non-reinforced ballasted railway was 0.2045 mm. The track settlement caused by the dynamic loading of the high-speed train was 24% less for the reinforced ballasted railway than for the non-reinforced ballasted railway. Hence, the inclusion of geotextile reduced the deformation rate.

Table 2: Comparison deformation in reinforced and non- reinforced ballasted railway

Variables	Values
Speed	350 km h^{-1}
Reinforced track (between sub-ballast and subgrade)	
Deformation (mm)	0.1228
Non-reinforced track	
Deformation (mm)	0.2045

Table 3: Comparison stress-strain in reinforced and non-reinforced ballasted railways

Variables	Values
Speed	350 km h^{-1}
Reinforced track (between sub-ballast and subgrade)	
Stress (Mpa)	0.1220
Strain	0.00117
Non-reinforced track	
Stress (MPa)	0.6776
Strain	0.0094

The maximum stress resulting from the dynamic load for a train speed of 350 km h^{-1} on reinforced ballasted railway was 0.1220 MP and the maximum plastic strain was 0.00117 MP. For non-reinforced ballasted railway the maximum stress for a train travelling at 350 km h^{-1} was 0.6776 MP and the maximum plastic strain was 0.0094 MP. Thus, the stress and strain values for reinforced ballasted railway were 70 and 76% less, respectively, than the values for the non-reinforced ballasted railway. This demonstrates the effectiveness of geotextiles in reinforcing the ballasted railway track (Table 2 and 3).

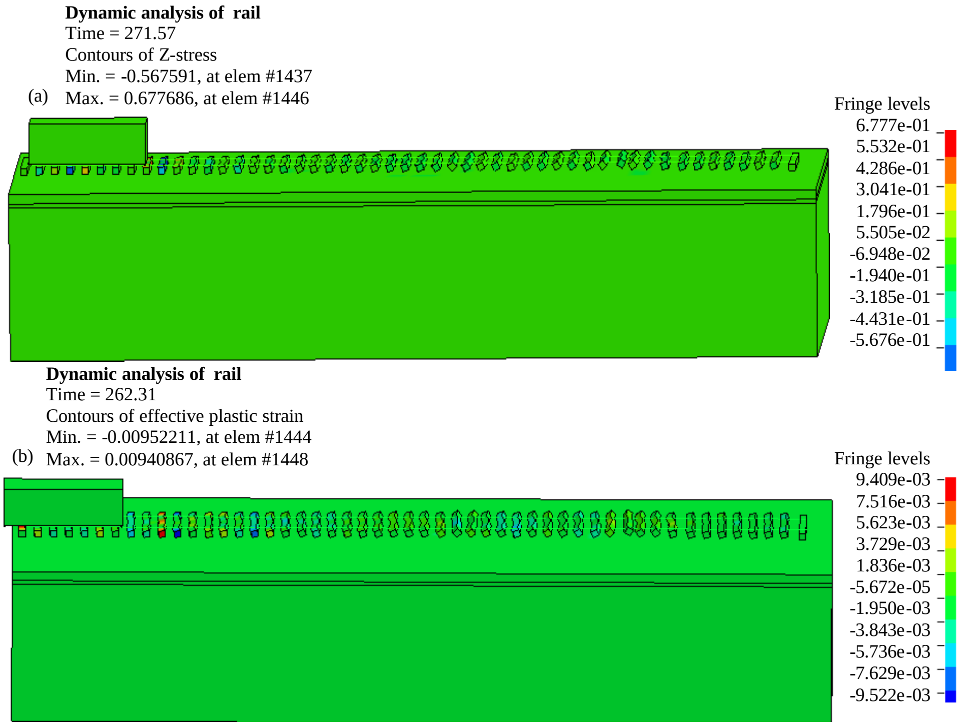

Fig. 7: a) stress in a non-reinforced ballasted railway for a train speed of 350 km h^{-1} and b) plastic strain in a non-reinforced ballasted railway for a train speed of 350 km h^{-1}

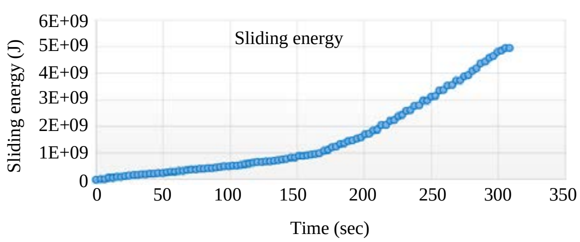

Fig. 8: Sliding energy

Sliding energy: The sliding energy measures the penetration of one component into others. Figure 8 shows the calculated sliding energy; the positive values show that the system was properly designed and modeled with no component penetrating others.

Contact forces: The contact between the wheel and the track is a basic element of railway vehicle dynamics. The geometric or kinematic and dynamic relationships in this contact and its mechanical behavior are crucial in calculating the contact force. Contact modeling using finite element analysis in LS-DYNA involved commands including CONTACT AUTOMATIC SINGLE SURFACE, CONTACT AUTOMATIC SURFACE and CONTACT TRANDUCER PENALTY; the results of modeling based on this method are shown in Fig. 9.

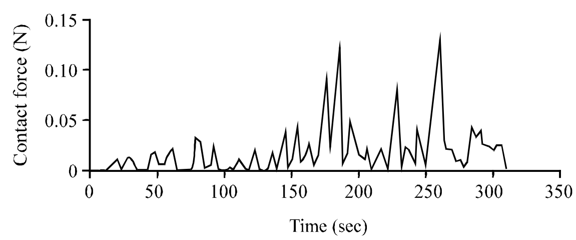

Fig. 9: Contact force

CONCLUSION

The use of geotextiles is a newly emerging field in civil engineering applications worldwide. Geotextiles are ideal materials for use in infrastructure construction including railways, roads and harbors. Geotextile use in reinforcement for base and subgrade layers has recently been identified as one of the best and most economical approaches to the construction of ballasted railway track on soft subgrades. Geotextiles provide a stiff material that maintains the full thickness and integrity of the soft subgrade throughout the service life of the railway.

High-speed ballasted railway track was modeled using the LS-DYNA finite element computer code. The geometry of the ballasted components of the high-speed railway track was modeled using LS-DYNA which includes a wide range of geometries for the simulations involved. Similarly, analysis of element types for various components of the high-speed railway utilized the LS-DYNA element menu. This provided very realistic and valuable output. Furthermore, the rail and sleepers were modeled as beam elements and the ballast, sub-ballast and subgrade as solid elements. The geotextile was considered a shell element as its thickness was very small compared with its other dimensions. The rigid element type was appropriate for the train as it is a non-deformable element.

LS-DYNA has keywords for modeling parameters including the forces, speed, traffic line, contacts, spring and damper and boundary conditions. The velocity of the train was defined using the PRESCRIBED MOTION keyword, the dead load/static load was defined using the LONDE_NODE SET keyword and the traffic line using the RAIL_TRACK and RAIL_TRAIN keywords. Contacts between parts, segments and nodes of the high-speed ballasted railway track were defined using the CONTACT_SINGLE-SURFACE, CONTACT0_SURFACE_SURFACE and CONTACT_TRANDUCER_PENALTY keywords. All defined keywords were prescribed in LS-DYNA.

As per the model analysis using LS-DYNA, the deformation rate for the reinforced ballasted railway was 24% less than non-reinforced ballasted railway track. Furthermore, the stress state for the reinforced ballasted railway was 70% less than that for the non-reinforced ballasted railway. Similarly, the strain state for the reinforced ballasted railway was <76% that for the non-reinforced ballasted railway.

Most soft subgrade ballasted railway tracks exposed to high-speed train loads deteriorate rapidly; such tracks require high-strength substructures to resist the dynamic responses. Geotextiles are effective materials for reinforcing soft subgrade ballasted railways. Numerical simulation using finite element analysis provides a potentially useful design method in the construction of reinforced soft subgrade ballasted railways.

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