Chapter 7
Sustainability of Railway Tracks

Sarvesh Chandra and Devanshee Shukla

Abstract The infrastructural growth of the railways has brought the railway track sustainability into a fresh perspective. Safe, stable, durable, and sustainable tracks are of paramount importance for the efficient function of the railways. In this paper, the development of the railway track from its inception to the present-day scenario has been presented. Numerous studies, conducted by researchers all over the world, that are aimed at studying the track response and improving its performance have been discussed. The analytical and numerical models developed to study the stresses and deformations in the track structure have been examined. It has been established that reinforcement of the track structure with geosynthetics reduces its settlement, increases the bearing capacity, and improves the drainage performance.

Keywords Sustainability • Railway track • Ballast-less track • Geosynthetics • High-speed trains

7.1 Introduction

Railways, since their inception, have inextricably acted as arteries establishing faster and more efficient connections between regions, paving the way for infrastructure growth and economic development. In today's fast-paced world, new and fast connections are required within any country to bring economic opportunities, growth, and prosperity to the country and its people.

The increase in passenger and freight traffic has ushered in an era of high-speed trains. The objective is for these trains to serve as an alternative to air travel. The axle loads and the speed of trains are increasing with time. To accomplish this, there is a need to build tracks that are safe, stable, durable, and sustainable. It is necessary to enhance the track structure sustainability and develop and employ technology that brings about reduced rates of deterioration and maintenance along with mitigating the environmental impact of vibrations, noise, and the materials used.

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7.2 Development of the Railway Track

Since the beginning of the railways, the ballasted track structure consisting of a framework of rails and sleepers supported on ballast has been most widely in use. The ballast layer rests on a sub-ballast layer, which transmits the load over the subgrade. The principle of this track structure has evolved over time and still continues to do so in order to incorporate elements that work to increase its durability and stability and reduce the maintenance requirements and cost.

Sleepers made of timber were used for almost two centuries after the birth of the railway track (refer Fig. 7.1). The properties of wood were suited to provide a resilient track with good dynamic vibration absorption capacity. The wooden sleepers were light and easy to transport and required little or no specialist equipment for fastening and subsequent maintenance. Gauge-width control was easily possible with timber sleepers, and the damage in case of derailments was also less.

However, these sleepers were replaced over time with alternative materials due to their short service life, susceptibility to fire, decay, wear and tear, and most importantly the scarcity of wood.

Cast-iron sleepers followed timber sleepers. These were extensively used in the Indian Railways for almost five decades and provided better longitudinal and lateral stability to the track and had a longer life span of 35–50 years.

The use of cast-iron sleepers was however discontinued due to its poor damping characteristics of high frequency vibrations, unsuited to modern maintenance methods and excessive damage caused during derailment.

The nonavailability of suitable species of timber and the inherent disadvantages associated with cast-iron sleepers brought in steel as a suitable contender in the construction of sleepers. Around 30 % of the track in India is laid out on steel sleepers. Steel sleepers came with a long service life, had great dimensional accuracy, were easy to manufacture, and had low maintenance requirements.

Fig. 7.1 Ballasted track with timber sleepers

The high cost of steel was the main disadvantage of this variant of sleeper material.

The use of concrete as a sleeper material gained significance in post-Second World War era due to improvements in concrete technology, better understanding, and use of prestressing techniques. The scarcity of timber and relatively high cost of steel were also instrumental in the turn toward RCC and prestressed concrete sleepers. Today, these sleepers are most widely used throughout the world. These are relatively easy to manufacture, have long service life, and provide better freedom to design and construct.

The two main types of concrete sleepers in use are twin-block sleeper and mono-block sleeper. Twin-block sleepers consist of two blocks of reinforced concrete connected by a coupling rod or a synthetic pipe filled with reinforced concrete. These sleepers have been used on many TGV tracks in France. Mono-block sleepers are based on the shape of a beam. They are of lower cost, have little susceptibility to cracking, and can be prestressed.

The latest development in the field of railway track is use of composite sleepers. These sleepers are mainly HDPE based, and many also contain other variants of waste plastic such as PVC, polyethylene, etc. As the sleepers are made from nonbiodegradable material, they have a long service life of 40–50 years. These sleepers are considered to be better replacement of traditional sleepers as these have flexibility equivalent to that of timber sleepers and cost significantly less. The manufacture of composite sleepers ensures a proper use of waste plastic, which is otherwise creating environmental hazards. The performance of the sleepers in static load test, impact load test, and dynamic load test has been evaluated and found to be satisfactory. Thus, the Indian Railways has used these sleepers on some of its tracks.

Traditional ballasted tracks undergo deterioration due to the pressure exerted by the passing load. The amount of track deterioration is directly proportional to the amount of tonnage passing and its speed over the track. This makes regular maintenance necessary. To address the drawbacks associated with the traditional ballasted track structure, new developments are being introduced to improve the efficiency and reduce the maintenance requirements. Some such modified designs are wide sleepers and frame sleepers.

Wide sleeper track superstructures were first attempted in China, former Czechoslovakia, and former East Germany (refer Fig. 7.2). It was Germany, however, that perfected the design and construction of the wide sleeper track.

The wide sleeper is 2.40 m long and 57 cm wide with sleeper weight of 560 kg, which is double the weight of the standard sleeper. With an axle load of 22.5 tonnes, the average surface pressure works out to be 2 kg/cm^2, which is nearly half of the average surface pressure in case of the standard sleeper. This results in reduced pressure on the track and homogeneous distribution of pressure onto the ballast. Due to the high supporting area, there is less strain on the subsoil and substructure along with an increase in the sideways' stability of the track. This results in lesser maintenance frequency and costs. The construction costs for such tracks are

Fig. 7.2 Ballasted track with wide sleepers

10–20 % higher than for normal tracks, but these additional costs can be compensated in the medium term through lower maintenance cost requirements.

Frame-sleeper structures have been developed and implemented mainly in Austria. The frame sleeper consists of cross sleepers placed at regular distances, combining a continuous longitudinal beam with cross members. These sleepers replace the load-transmitting structure of a traditional ballast track by a girder grid system. The wheel load is transmitted onto the ballast bed in a continuous manner, thereby reducing the pressure under the sleepers significantly. These sleepers offer very high lateral resistance and frame stiffness and yield reduced settlements, thus making the track more durable.

The traditional ballasted track systems, when used in high-speed operations, have been found to be maintenance intensive. Since maintenance operations are becoming more and more difficult to carry out due to increased freight and passenger traffic, the conventional tracks pose a serious drawback. Ballast-less tracks or slab tracks have much lower maintenance requirements and provide more stability, passenger comfort, and durability and are the preferred option for light rail as well as high-speed lines.

Slab tracks have numerous advantages over ballasted tracks. The need for maintenance in these tracks is minimal. They have a long service life of 40–50 years. They provide high lateral and longitudinal stability, thereby reducing the deviations in track alignments. Slab tracks are highly suited for locations such as tunnels and viaducts where the acceptable settlement criteria are very stringent. In India, slab tracks are used by DMRC and in recently completed Pir Panjal Railway Tunnel in J&K line (Fig. 7.3).

The construction costs of slab tracks are considerably higher than that of ballasted tracks. However, this factor does not pose a major drawback as the investment mindset is now tilting from focusing solely on initial investment costs to adopting the robust principle of life cycle costing. This principle makes comparative cost assessments over a period of time, taking into account the initial capital costs as well as future operational and asset replacement costs.

With India taking significant steps in the direction of establishing high-speed railway (HSR) lines, the transition from ballasted to ballast-less tracks is inevitable.

Fig. 7.3 View of a slab track in Germany

However, the railway track network in India is very extensive, and it is not feasible to convert the entire existing ballasted track network to a slab track network. Therefore, it is imperative that technology capable of making the existing tracks sustainable, durable, and better suited to faster trains is explored and focused upon.

7.3 Development of Numerical Models to Study Track Sustainability

The structure of the railway track can be divided in two parts – the superstructure and the substructure. The track superstructure consists of the rail, sleeper, and fastenings, while the ballast, sub-ballast, and the subgrade constitute the substructure. It was realized that the sustainability of the track structure depends mainly on the performance of the substructural components. Thus, over time many researchers have attempted to develop reliable numerical models of the track structure to study the stresses and deformations that the track structure is subjected to due to applied load. Some of these models have been discussed in the subsequent sections.

Mathews (1958) analyzed the dynamical problem of vibrations of a beam resting on an elastic foundation. The beam was assumed to be uniform and of infinite length. It was subjected to an alternating load whose point of application was considered to move along the beam at a constant velocity. The author investigated the nature of vibrations in the system when damping was absent and defined the critical parameter characteristic of the system. The general mathematical solution to the problem of a beam subjected to a force whose point of application moved along the beam was obtained through this study.

Fryba (1972) studied the response of an infinite elastic medium subjected to a moving load by considering all possible values of the velocities of the moving load.

Viscous damping was considered to be present in the system. The solution was obtained using the technique of triple Fourier integral transformation. The study identified a critical speed for the moving load by determining the equivalent stiffness of the supporting structures. It was shown that the deflections of the beam increased asymptotically at the critical speed.

Duffy (1990) studied the response of an infinite railroad track when subjected to a moving and vibrating mass. The railroad track was modeled as an elastic beam lying on a Winkler foundation, and the vibrations caused by the passing of a moving, vibrating load were analyzed. Duffy (1990) obtained solutions for moving as well as stationary vibrating loads as a function of three parameters, namely, the mass of the load, its driving frequency, and the physical properties of the track.

It was concluded that for a stationary vibrating load, resonance occurred at lower frequencies when the mass of the load was increased, whereas for a moving vibrating load, resonance occurred at lower frequencies when the mass and velocity of the load were increased.

A number of multilayer track models were developed since 1970s to analyze and determine the stresses and deformations in the track structure.

Chang et al. (1980) developed one such model named GEOTRACK, which was an elastic, multilayer, three-dimensional model capable of analyzing stresses and strains in all the major track components, such as rails, sleepers, ballast, sub-ballast, and subgrade. The impact of factors like applied loads; thickness and properties of the ballast, sub-ballast, and subgrade; and track geometry, on the response of the track structure, was evaluated through this model.

Selig and Waters (1994) used the GEOTRACK model and performed an extensive parametric study of deviator stress present in the subgrade. The study established that the deviator stress in the subgrade was the most influenced parameter affected by the granular layer thickness and resilient moduli of the granular layers and the subgrade. It was shown that the deviator stress decreased with an increase in thickness and resilient modulus of the granular layer (Fig. 7.4).

Shahu et al. (1999) developed a three-dimensional linear elastic finite element model to investigate the effect of various track parameters, such as major principal

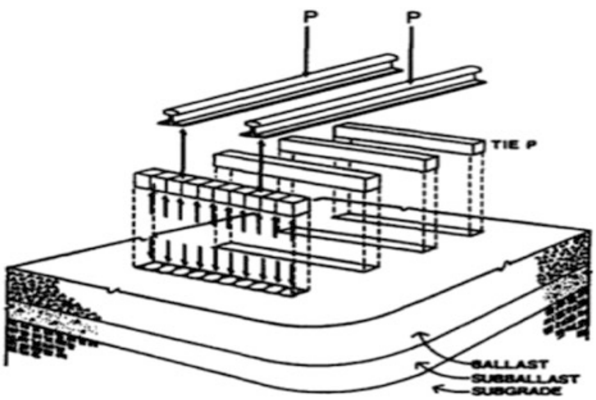


Fig. 7.4 Schematic representation of track forces and elements in GEOTRACK model (Chang et al. 1980)

stresses, deviatoric stresses at subgrade level, displacement of the sleeper, and track modulus, on the overall track response.

The model adopted in the study was a 3D20N element that used 20-noded isoparametric brick elements for various track components, one-dimensional beam elements for the rail elements, and 16-noded zero-thickness surface elements to simulate the interface between different layers. The authors, using a practical range of industry applicable track variables, also performed a detailed parametric study of the track response.

The study concluded that the most influential track response parameter was the subgrade modulus. The sub-ballast depth, rail moment of inertia, and tie spacing were found to be next most important factors that influenced the track responses (Fig. 7.5).

Shahu et al. (2000) developed a rational design method to determine the thickness of the formation of a railroad track (refer Fig. 7.6). The design approach adopted was based on keeping the maximum deviator stress induced in the subgrade layer below the threshold value of stress of the subgrade soil by providing a suitable thickness of the track formation.

The method developed by the authors used recent developments in the evaluation and prediction of threshold stresses and three-dimensional finite element modeling of the railway track to predict the stresses induced in the system. This

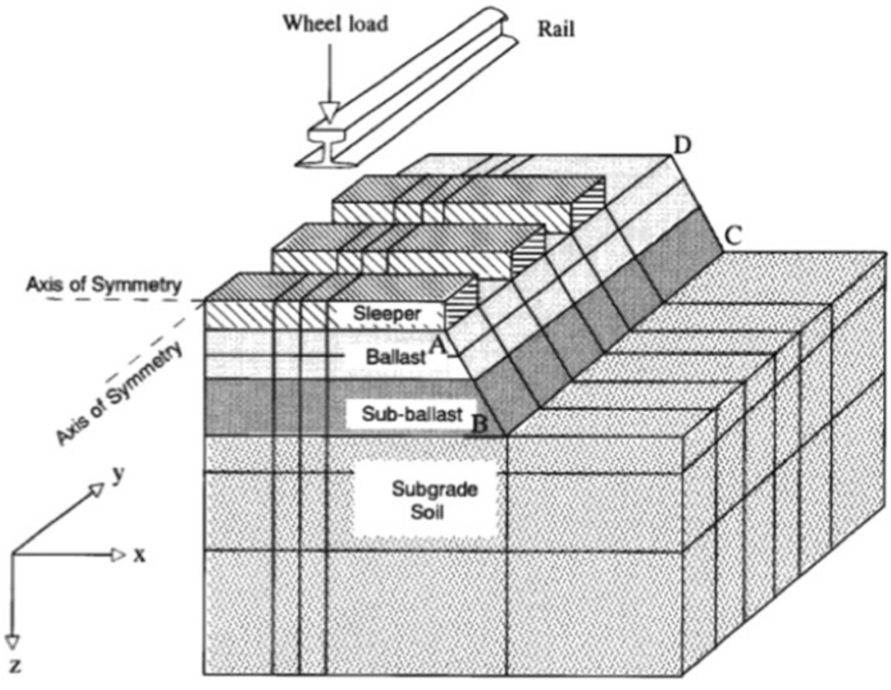


Fig. 7.5 Schematic representation of the 3D track model proposed by Shahu et al. (1999)

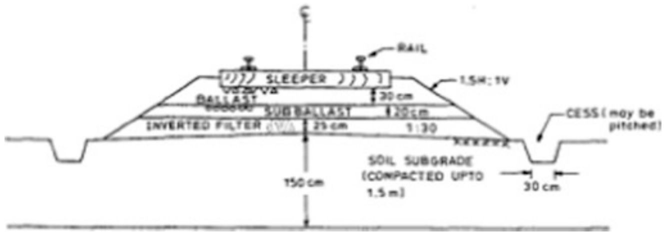


Fig. 7.6 Schematic representation of the railway formation proposed by Shahu et al. (2000)

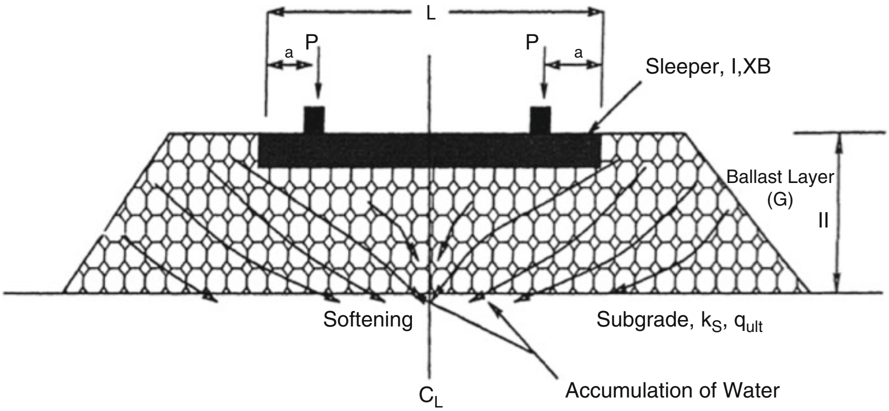


Fig. 7.7 Schematic representation of railway sleeper-ballast-subgrade system modeled by Ghosh (2001)

method, unlike previously existing methods, was applicable to various soil types and different properties of the ballast and sub-ballast layers and was found to be highly suited in cases of high-speed traffic and heavy axle loads.

The study provided a simple procedure for quick evaluation of the resilient modulus and threshold stress in the subgrade soil. The performance of an actual track in the field was studied to develop this method.

Ghosh (2001) studied the effect of softening of the subgrade, due to percolating rainwater, on the response of the railway track. It was known that 95 % of failure or maintenance problems in tracks were due to the poor bearing capacity of the subgrade and gave rise to ballast penetration and mud pumping which affected the track geometry.

The railway sleeper-ballast-subgrade system was idealized as a two-parameter Pasternak model (refer Fig. 7.7). The effect of subgrade softening on the modulus of subgrade reaction was defined as a linear and nonlinear variation. The solution was obtained using a finite difference solution scheme.

The study concluded that subgrade softening affected both deflection and bending moment in the railway sleeper, with maximum deflection being observed at the location of maximum softening, i.e., at the center of the sleeper. The remedial design solution proposed was to introduce a geosynthetic layer at the interface of the sub-ballast and subgrade.

Singh (2002) studied the steady-state response of a uniform beam placed on an elastic foundation and subjected to concentrated moving load at a constant speed.

The authors idealized the system as an infinite Euler-Bernoulli beam of constant cross section resting on an elastic foundation modeled using both one- and two-parameter models. The response of the foundation was attained analytically to get closed-form solution for different cases of speed of moving load and damping present in the beam.

The study presented numerical results of the system at subcritical and supercritical speed in terms of its responses such as beam deflection, bending moment, and shear force in the system for different load speeds, damping, and foundation modeling.

Maheshwari (2004) carried out an extensive study to determine the response of beams resting on reinforced granular soil systems and subjected to static and moving loads. The study was aimed at developing a generalized model applicable to railroad tracks, foundations, etc.

In the first model developed by the author, the foundation was analyzed as a beam of finite length subjected to a static load (refer Fig. 7.8). The geosynthetic reinforcement was idealized as another beam in order to incorporate its bending stiffness. The two beams were considered to be of the same length. The governing equations for the model were solved using appropriate boundary and continuity conditions, and a closed-form analytical solution was obtained for the response of the model. The analysis concluded that the placement of the reinforcement, relative stiffness of the foundation soil, and relative flexural rigidity of the beam affected the model response significantly.

The author developed two more models with the foundation modeled as an infinitely long beam subjected to a load moving at a constant velocity (refer Fig. 7.9). Two conditions were studied in the above setup – first, the foundation beam was assumed to be in contact with the ground surface, and second, the

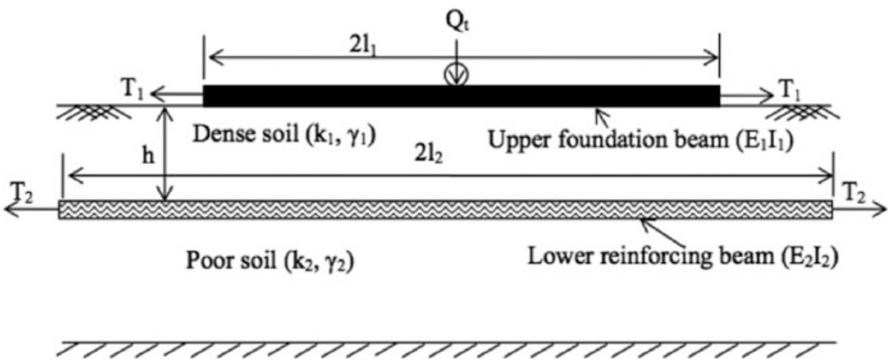


Fig. 7.8 Schematic representation of the two-beam model proposed by Maheshwari (2004)

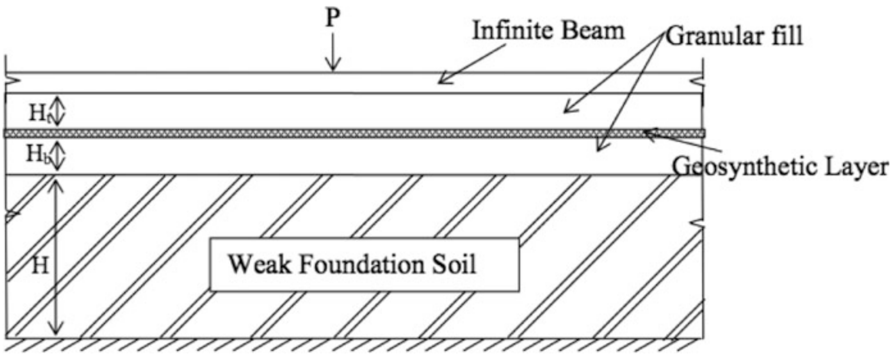


Fig. 7.9 Schematic representation of the model proposed by Maheshwari (2004)

separation between the beam and ground surface was considered. The geosynthetic was modeled as a rough elastic membrane, inextensible in nature in one model, and as an extensible membrane with tensile stiffness, in the other model. The analyses of both models were carried out by the finite difference solution scheme. The responses of both models were found to be significantly affected by the intensity of the applied load, velocity of the load, and relative compressibility of the granular fill.

Vihari (2005) proposed a new design approach to determine the thickness of the granular layer in a railway track, which took into account the effect of shear strength parameters of the foundation soil and the foundation coefficient. The design approach adopted was stress controlled which focused on the strength parameters.

The author adopted a design method that considered the mode of failure of the subgrade soil to be rotational failure about a point just below the end of the sleeper (refer Fig 7.10). A C code was developed to determine the factor of safety of the track and soil, which was then used to evaluate the thickness of the granular soil layer.

The study established that the factor of safety was linearly related to the shear strength parameters of the foundation soil and inversely related to the speed of the train. The depth of the granular fill was found to be inversely related to the shear strength parameters of the soil and highly influenced by the foundation coefficient.

Chaudhari (2012) performed a study to formulate the settlement response in a railway track structure reinforced with a geosynthetic layer and compare it with the unreinforced track model.

The ballast and sub-ballast were modeled as Pasternak shear layers with a prestressed geosynthetic placed at the interface of the two layers. The subbase was idealized as a layer of Winkler springs, and the subgrade was modeled as a viscoelastic medium represented by Burger elements (refer Fig. 7.11). A uniformly distributed load was applied to the system, and the governing equations obtained for the settlement response were solved using a finite difference scheme.

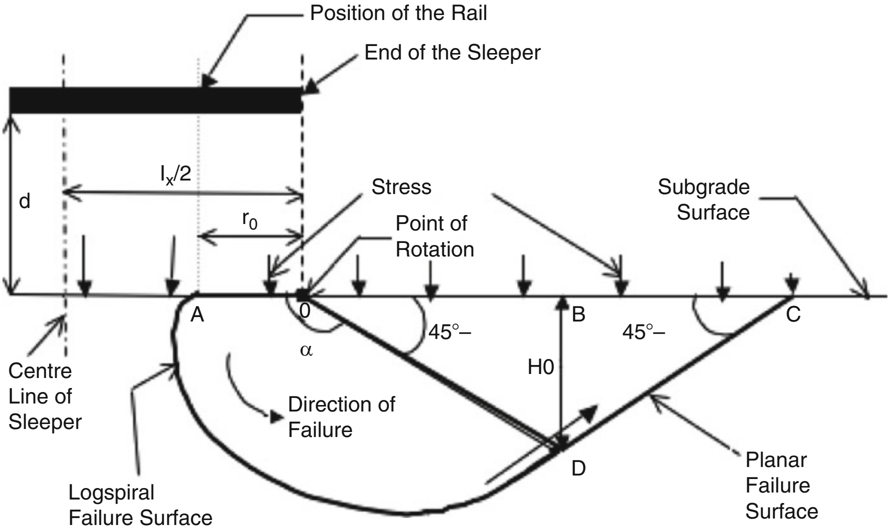


Fig. 7.10 Schematic diagram of failure mode in the subgrade soil proposed by Vihari (2005)

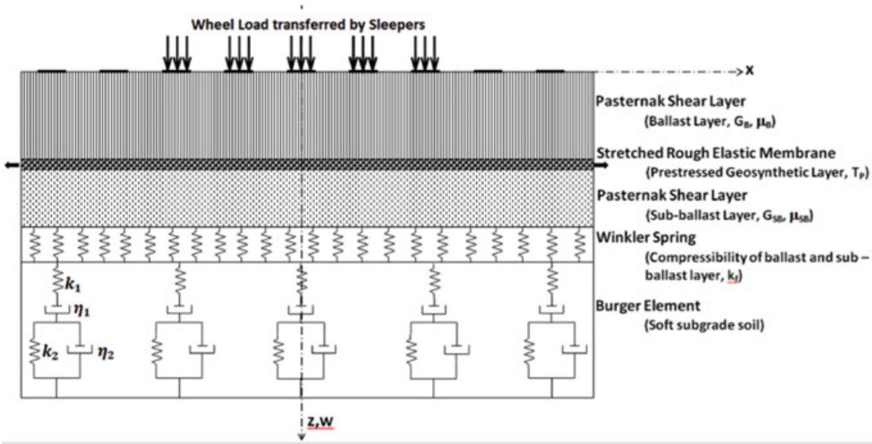


Fig. 7.11 Schematic representation of the model proposed by Chaudhary (2012) for railway track modeling

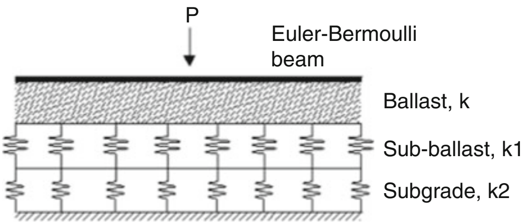
The study concluded that settlement depended on a number of factors, namely, the presence or absence of reinforcement, the thickness of the ballast and sub-ballast layers, and the shear moduli of the two layers. The presence of geosynthetic reinforcements, greater thickness, and higher shear modulus of the ballast and sub-ballast resulted in lower settlements in the track structure upon application of loads.

Prasad and Chandra (2014) carried out a study to investigate the response of a railway track when subjected to a moving load. The track was modeled as an Euler-Bernoulli beam resting on a two-parameter foundation model with the sub-ballast and subgrade being represented by two layers of Winkler springs (refer Fig. 7.12). The finite difference solution scheme was used to determine the uplift, settlement, and bending moment caused due to variations in parameters such as velocity of the moving load, damping, and stiffness of the subgrade.

It was found that with increase in stiffness of the subgrade layer, the point of maximum deflection shifted behind the applied load. Changes in the stiffness of the subgrade layer were found to have an insignificant effect on the behavior of the beam. The results were found to be consistent with those obtained by Mallik et al. (2006).

Kumar (2013) conducted one of the most recent analytical studies on the railway track structure. The author developed a new model to study the behavior of a traditional ballasted railway track, reinforced with a geosynthetic layer and subjected to a moving load at a constant velocity (refer Fig. 7.13). The moving load was due to a single axle load moving at a constant velocity. The track substructure included the ballast, sub-ballast, and subgrade layer. The rail was idealized as an Euler-Bernoulli beam, while the ballast and sub-ballast were modeled as Pasternak shear layers resting on the subgrade, which was represented as a series of Winkler springs.

Fig. 7.12 Schematic representation of the model developed by Prasad and Chandra (2014)



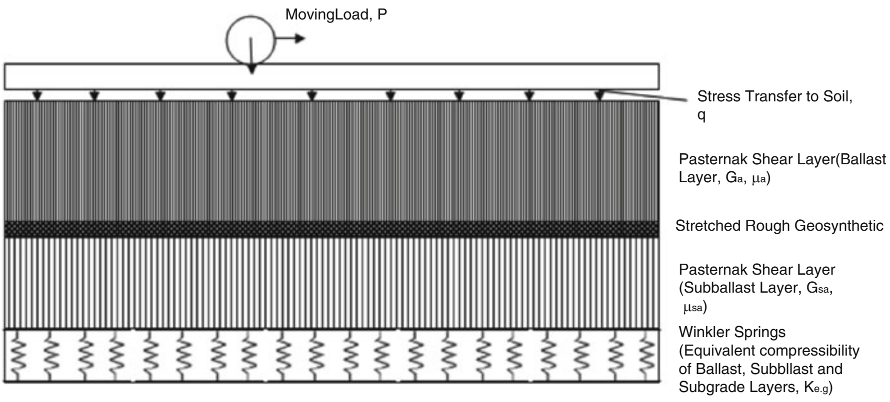


Fig. 7.13 Schematic view of the model proposed by Kumar (2013)

Two governing differential equations were obtained for the system. The first equation was the beam equation modified according to the reinforced model, while the second equation dealt with the development of tension in the geosynthetic membrane. The two equations were solved simultaneously by the finite difference solution scheme using an iterative approach.

The author studied the effects of variation of different parameters on the track system. The system was analyzed with and without a geosynthetic layer. When the geosynthetic was taken into consideration, it was analyzed with and without pretension, and the corresponding results and track responses were compared. The results obtained were validated with those obtained by Singh (2002).

For the parametric study undertaken by the author, axle loads varying from 20 tonnes to 200 tonnes were considered. The range of values was chosen to be wide because even though currently the axle load on Indian railway tracks is approximately 30 tonnes, with the advent of high-speed trains, it is likely to increase up to 200 tonnes and more. Thus, the track responses for high-speed scenarios were also taken into consideration.

The study concluded that the nondimensional displacement varied linearly with the increase in the load intensity for the unreinforced as well as the reinforced case. However, in the case of the track reinforced with a pretensioned geosynthetic, the settlement was observed to be 5–10 % less than that in the unreinforced and without pretensioned cases. It was found that the reinforcement had a more pronounced effect for lower thickness of the ballast and sub-ballast layers, lower values of shear moduli for the ballast and sub-ballast, and higher load values.

Through the author's analysis, it was established that greater pretension in the membrane results in lower values of the nondimensional displacement in the model. It was also shown that application of pretension helps make the design more economical by reducing the required depth of the ballast and sub-ballast. Thus, the study proposed a feasible and relatively economical means of making the existing tracks more suited to high-speed trains and increasing their sustainability in the long run.

7.4 Conclusions

In this paper, the evolution of the railway track structure, from its beginning up to the present-day developments, has been presented. The efforts of various researchers to develop numerical and analytical models that predict the behavior of the railway track system under external loads have been discussed. The studies indicate that the performance of the railway tracks exhibits a substantial improvement, with respect to reduced settlements, increased bearing capacity, and improved drainage, when reinforced with geosynthetics. The simplicity associated with the modeling and analysis of geosynthetics and their economic viability makes them a suitable option. The scope of such studies is expanding, and more efforts are being directed to find viable solutions that increase the track performance and its sustainability.

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