Chapter 19
Deformation Modulus Characteristics of Cyclically Loaded Granular Earth Bed for High-Speed Trains

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19.1 Introduction

The development of a high-speed rail network has become a priority for every developed and developing country. As it is a fact that the transportation sector is the backbone of every economy, efforts are being made on an everyday basis to develop and find a sustainable approach for high-speed trains. India has the fourth-largest rail network in the world and since India is a developing economy, a new and efficient design methodology is a must need, to meet the growing needs of the country. The existing rail network of India still works at comparatively slower speeds and the design methodology has not been changed in a quite some time and if we compare the old (GE-1) and new design code (GE-14) (2007) we can find that the height of the embankment has been increased with the inclusion of the blanket layers. This is a common practice in most of the developing countries where the height of the embankment is increased to meet growing load and speed requirements. However, most of Europe's rail design methodologies are based on the deformation modulus. Indian Railways have also adopted a similar approach of UIC 719R (2008) in establishing the design as indicated in the GE-14 code (2007) of Research Design and Standard Organization (RDSO). As the situation stands there are no solid provisions to upgrade the existing design methodology or any evidence supporting the suitability of embankment for higher speeds and especially for the existing rail network. So, there is an interest in improving the railway embankment for higher speed as well as economical designs that can be implemented easily in the field on new as well as existing tracks. Many researchers have investigated the improvement of railway embankment by using various approaches such as chemical stabilizers, ground treatments with lime or cement and more recently as reinforcements. The use of geogrids is becoming more and more prominent in roads and now in railways too. The very first major contribution in the

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field of reinforcement for railways came from Jain and Keshav (1999), where series of empirical full-scale tests were conducted with the use of geogrids as reinforcements. The geogrids were installed at the bottom and within the embankment. The results were of great significance as the type of loading used for the experiments was of dynamic in nature (as a function of axle loads). As per the results reported, a single layer of geogrid reduces 40–20% of dynamic loads and two layers of geogrid reduce 60–30% at a depth of 0.90 m. Similarly, Shin et al. (2002) reported a total reduction of 47% in the settlements when one layer of geogrid and one layer of geotextile were used and also reported the critical number of cycles 'N_{cr}' after which no further settlements takes place in railway embankment. Indraratana et al. (2005) further investigated deformation characteristics of railway ballast and formation of soil. Innotrack (2006) guidelines for subgrade reinforcement with geosynthetics describe in detail, the numerical, laboratory and field testing methods to improve the performance of ballast embankment. Static tests and lightweight deflectometer were used to calculate the stiffness of the embankment. Reported results showed the improvement of 15% in deformation modulus in the presence of geogrids when placed under the ballast instead of sub-ballast. In this article, results of cyclic plate load test as per DIN 18,134 (2001) are reported and compared to European design standards for high-speed trains guidelines. The plate load test is selected because it is simple, widely used for other earth structures as a measure of quality and is covered with precise norms for different countries. Very few researchers have tried to investigate railway embankment using this test as the basis of performance, as European countries have already set up high-speed networks and standards up to a speed of 300kmph based on established parameters from this test (e.g., RIL 836) (AG, DN 2014; Alamaa 2016). Emersleben and Meyer (2008) used static plate load test and falling weight deflectometer to report the benefits of Geocells in road embankments by evaluating the embankment stiffness. Recently Minazek and Mulabdic (2013) tried to establish the benefits of plate load tests in determining the stiffness of reinforced embankment by using gravels on various types of geogrids. More recently Puri et al. (2017) studied the effect of blending sand with clay in field conditions to improve the bearing capacity and reduction of settlements under repeated loading conditions. Similarly, Mamatha and Dinesh (2018) have studied soil aggregate system but in context to the road pavement based proving the reliability of DIN 18,134 guidelines.

19.2 Methodology

The apparatus consists of a rigid square steel box made by using hard grade steel plates. This open box consists of smooth parallel walls and a back wall. The dimensions of the box are 1 m × 1 m × 1 m enabling to represent the embankment up to 1 m in height. As per DIN 18,134, the test can be conducted on the metal plate capable of sustaining max. load applied. The size in this experiment was limited to 200 mm instead of 300 mm (usually used) to eliminate the boundary effect for horizontal pressure bulb (5B). The tank was supported with a rigid loading frame capable of generating a load of 250 kN fitted with an electronic ram, controlled manually. To read the settlements of the entire plate, square plate was used which was mounted with four dial gauges at each corner. As per DIN 18,134, the max. load to be imparted on the loading plate should be capable of generating a load intensity of 500 kN/m^2. The load applied should be completed in six stages with equal load increments until the max. load intensity is reached. During the unloading phase, the load shall be removed in three stages to 50%, 25% and finally to approx. 2% of the max. load before starting the next cycle. The test is terminated when either the max. the design load is achieved or the designated settlement is reached. As per DIN 18,134 for road construction purposes 5 mm settlement is set (DIN 2001) while no such value is available for railway embankment, a similar 5 mm settlement can be used as these experiments involve the soil embankment. The test set up can be seen in Fig. 19.1.

UIC 719 R and RIL 836 (Alamaa 2016) provide the guidelines to achieve minimum deformation modulus for railway embankments to sustain high-speed lines or up to 300 kmph. UIC 719R contains guidelines and standards of earthworks and trackbed construction of railways lines for all members of the international union of railways and RIL 836 is a German guidelines for earthworks and geotechnical structural design and maintenance. The deformation modulus for first and second loading cycles is calculated using below equation as,

$$Ev = 1.5 \times r \times \frac{1}{a_1 + a_2.\sigma_{0\,\max}} \tag{19.1}$$

whereas E_v = deformation modulus, r = radius of plate, $a_{1,}$ a_2 = constants from Eq. 19.2,

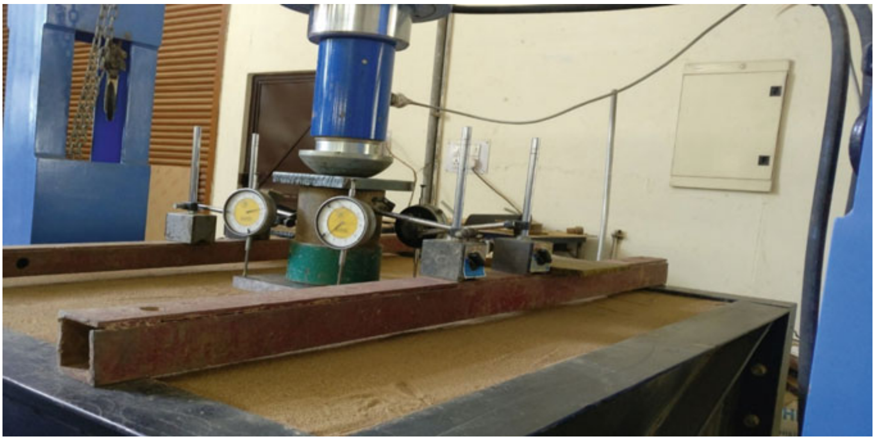

Fig. 19.1 Test setup used in the current experimental program

σ_{0max} = max. avg. normal stress below the loading plate in the respective cycle in MN/m^2.

The constants a_1 and a_2 can be calculated from the solution of second-degree polynomial equation for the settlement measurement as,

$$S = a_0 + a_1.\sigma_0 + a_2.\sigma_0^2 \tag{19.2}$$

whereas σ_0 = avg. normal stress below the plate in MN/m^2,
s = settlement of loading plate in mm,
a_0 = constant of second-degree polynomial in mm,
a_1 = constant of second-degree polynomial in mm/(MN/m^2),
a_2 = constant of second-degree polynomial in mm/(MN^2/m^4).

19.3 Materials and Preparation

The soil used for the blanket layer was cohesionless soil classified as silty sand (SM) whose grain size distribution is given in Fig. 19.2a. The ballast used in the test was provided by Indian Railways which was of the same gradation as used in actual railway formations having grain size from 20 to 65 mm. The grain size distribution of the same is given in Fig. 19.2b. The materials used to represent the sub-ballast that follows the gradation provided by the Indian Railways manual comprising of 4.75 mm grain size to 20 mm. Few further evaluated properties of the material used are shown in Table 19.1. Since the height of the tank is 1 m, the max. height for the subgrade layer can be 1 m and as per GE-14 the thickness of the soil subgrade is 500 mm for SQ2 and SQ3 categories for an axle load of 25 T. SQ1,

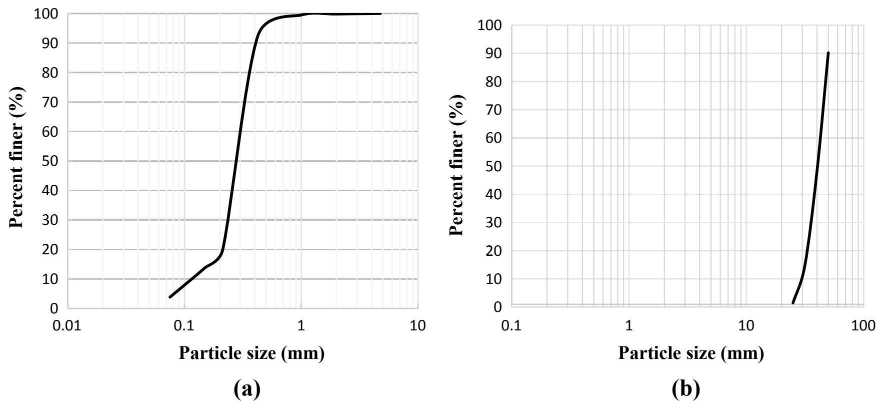

Fig. 19.2 **a** Particle size distribution curve for blanket layer **b** Particle size distribution curve for ballast

Table 19.1 Gradation and compaction strength parameters of material used

Material	Coeff. of uniformity (C_u)	Coeff. of curvature (C_c)	Classification	Density
Soil	2	1.38	SM	53% (I_d)
Ballast	1.5	0.9	Highly angular	16.7 (kN/m^3)

Table 19.2 Classification of soils and modulus as per GE-14, Indian Railways

Type	Classification	Blanket thickness (cm)	EV_2 for subgrade (MPa)	EV_2 for blanket layer (MPa)
SQ1	Fines >50%	100	45	100
SQ2	Fines 12–50%	75	45	100
SQ3	Fines <12%	60	45	100

SQ2 and SQ3 are the soil classification as per RDSO guidelines based on the percentage of fines as mentioned in Table 19.2, hence SQ3 represents a very good quality soil, SQ2 is average quality and SQ1 bad quality (usually avoided). Now as per RDSO guidelines, the thickness of the subgrade layers is decided based on the soil quality as mentioned in Table 19.2.

Apart from thickness GE-14 also mentions min. EV_2 (as per DIN 18,134) for subgrade layers as well as sub-ballast which can be seen in Table 19.2. From the objective of sustaining loads from the train, the height of the embankment comes to be in the order of 3.4–3.6 m from the ground level which ascertains lots of material (especially soil and aggregates). The study serves as a check to measure the quality of the subgrade for the mentioned design criteria as per GE-14. By following the stress isobar concept, the min. thickness for the soil subgrade in the tank was worked out to be 400 mm and which can be raised to 1000 mm. The plate load test was conducted and EV_1 and EV_2 were calculated to match the min. required values in GE-14 and to evaluate the height of embankment required based on deformation modulus values. Once the subgrade thickness is fixed, the inclusion of the blanket layer and ballast layer was also added to calculate the total height of the embankment.

19.4 Results and Discussion

The first few tests were conducted only on the soil as subgrade to be used in the embankment. The minimum possible thickness of 400 mm was achieved in the tank. Soil compaction is one of the most influential tasks while conducting plate load tests in the laboratory. The compaction effort was kept to 'heavy compaction' with the use of metal hammer weighing 8 kg. and was used to compact a single layer of 100 mm. Since the hammer used was a manual compactor, the number of blows can be increased to achieve heavy compaction. The relative density achieved for this type of soil was 53%. A preload was applied to the plate before the start of the test, generating the intensity of 10 kN/m^2 as per the recommendation of DIN 18,134. The dial gauges were reset to zero after the application of the preload before tests were performed. Table 19.3 shows the results that were obtained after the completion of the test program. The calculation of the deformation modulus was performed as per Eqs. 19.1 and 19.2. To solve for the constants a_1 and a_2, three additional equations were used which were based on the settlement and load for each step of the loading (total six steps) as observed in each test and are as follows:

$$a_0.n + a_1 \sum_{i=1}^{n} \sigma_{0i} + a_2 \sum_{i=1}^{n} \sigma_{0i}^2 = \sum_{i=1}^{n} s_i \quad (19.3)$$

$$a_0 \sum_{i=1}^{n} \sigma_{0i} + a_1 \sum_{i=1}^{n} \sigma_{0i}^2 + a_2 \sum_{i=1}^{n} \sigma_{0i}^3 = \sum_{i=1}^{n} s_i \sigma_{0i} \quad (19.4)$$

$$a_0 \sum_{i=1}^{n} \sigma_{0i}^2 + a_2 \sum_{i=1}^{n} \sigma_{0i}^3 + a_2 \sum_{i=1}^{n} \sigma_{0i}^4 = \sum_{i=1}^{n} s_i \sigma_{0i}^2 \quad (19.5)$$

After finding a_1 and a_2 from solving the above equations, EV_1 and EV_2 are calculated. Table 19.3 shows the results of tests conducted on various combinations of the embankment layers. The test was conducted at the minimum possible thickness of subgrade which was 400 mm and then increased to 500 mm to be on the safer side because of the stress isobar concept. Since the required EV_2 for the

Table 19.3 Deformation modulus values on the ballasted embankment in the laboratory

Thickness (mm)	EV_2 (MPa)	IR specification	Remarks
Subgrade (400)	61.47 > 45	Min. required EV_2 is 45 MPa	400 mm thickness is capable of required EV_2
Subgrade (500)	68.86 > 45	Min. required EV_2 is 45 MPa	500 mm thickness is capable of required EV_2
Subgrade (500) + blanket (200)	86.54 < 100*	Min. required EV_2 is 100 MPa	Required thickness of blanket should be increased
Subgrade (500) + ballast (300)	111.91 > 100*	Min. required EV_2 is 100 MPa	800 mm thickness capable of required EV_2
Subgrade (500) + blanket (200) + ballast (300)	138.94 > 100*	Min. required EV_2 is 100 MPa	1 m embankment, no EV_2 specifications for the inclusion of ballast from IR

* minimum EV_2 at top of blanket layer for 3.6 m high embankment as per Indian Railways

subgrade as mentioned in RDSO's GE-14 is 45 MPa and tests conducted show a value of more than 60 MPa, 500 mm thickness was selected as min. thickness of the subgrade. In the next step, the blanket material was added having a total thickness of 200 mm and then ballast material having a thickness of 300 mm instead of 350 mm (IR specifications) was added at the top making the total height of the embankment as 1 m. From Table 19.3, it is clear that the minimum required values set by IR are not directly linked to the height of the embankment and in most cases, the height of the embankment is much more than the required height based on deformation modulus values. To compare any existing recommendations from around the world, France's railway design requirements (Réseau ferré de France 2010) can be used where the design principle for ballasted track requirement for speeds up to 300 kmph is already working. The value on top of the embankment for the ballasted track is recommended to be 120 MPa, and the total height of the embankment is 900 mm(minimum) to 1200 mm (maximum) (Réseau ferré de France 2010). The availability of such types of standards and guidelines provides authenticity to these test trials and can help to achieve better and efficient designs. On comparison, it can be seen that deformation modulus of the order of 120 MPa can be achieved and embankment can be made fit for speeds up to 300 kmph. Also, it is evident that the height of the embankment is not a factor in achieving required embankment for high-speed trains.

Now, based on the current study, the required thickness based on the EV_2 values can be adopted as 800 mm and if blanket material is to be used thickness will be 1 m. Currently, as per GE-14, the minimum height of the embankment works out to be 3.45 m and the maximum is 3.6 m. On comparing with the height of the embankment which satisfies the min. required EV_2 values as per the current study, the percentage decrease can be calculated as,

$$\text{Original height of the embankment as per IR specification} = 3.45\,\text{m (min. height)}$$
$$\text{New height of the embankment as per current study} = 1\,\text{m (max. height)}$$
$$\text{Difference in height} = 2.45\,\text{m}$$

$$\text{Percentage decrease} = \frac{\text{difference in two number}}{\text{original number}} \times 100 = 71.01 \approx 71\%$$

19.5 Conclusions

The current study is an attempt to evaluate existing design methodology as adopted by Indian Railways using a cyclic plate bearing test as per DIN18134. The GE-14 code of RDSO establishes the height of embankment and different thicknesses based on the deformation modulus values based on this plate bearing test. The same test has been conducted in the laboratory on the various thickness of different layers (subgrade, blanket and ballast) of the embankment and the following conclusions can be made:

1. To meet the required deformation modulus, the height of the embankment adopted by IR can be reduced.
2. The total reduction in the height of the embankment based on the deformation modulus values is nearly 70%.
3. Due to a reduction in the embankment, construction time and mining material can be prevented from overusage.
4. Since existing design methodology is based on UIC 719R, a new methodology based on deformation modulus can be used as similar methodologies are adopted by European countries.
5. Based on the calculated values of deformation modulus in the laboratory, it can be assumed that based on the design values of deformation modulus (from RIL 836 or LGV), a track can be declared fit for high speed up to 300kmph.

After conducting this study, it is clear that the design methodology needs to be upgraded as per the growing requirements of the country. Merely increase in the height of the embankment will not meet the increasing load and speed demands of the second most populated country in the world. In the future, studies can be taken for use of reinforcement like geogrids under ballast and blanket will help further reduction in height of the embankment and will improve the quality of railways embankment for higher loads and speeds.

References

Alamaa A (2016) High-speed railway embankments: a comparison of different regulations

AG, DN (2014) RIL 836 Erdbauwerke und geotechnische Bauwerke planen, bauen und instand halten [Earthworks and geotechnical structures design, construction and maintainance]. Code. DB Netze AG, Frankfurt am Main, Germany, p 530 (in German)

DIN 18134:2001–09: Determining the deformation and strength characteristics of soil by plate loading test, Deutsche Institut für Normung (2001)

Emersleben A, Meyer N (2008) The use of geocells in road constructions over soft soil: vertical stress and falling weight deflectometer Measurements. In: Proceedings of 4th European geosynthetics conference, paper 132, Scottland

GE-14- RDSO- Guidelines for blanket layer provision on track formation. Design and Standard Organisation (RDSO), Ministry of Railways, India (2007)

Indraratna B, Sahin MA, Salim W (2005) Use of geosynthetics for stabilizing recycled ballast in railway track substructures. In: Proceedings of NAGS 2005/GRI 19 Cooperative Conference, 2005, pp 1–15. North American Geosynthetics Society, USA

Innotrack Integrated Project No. TIP5-CT-2006–031415: D2.2.6. GL, Guideline for subgrade reinforcement with geosynthetics (2006)

Jain VK, Keshav K (1999) Stress distribution in railway formation-A simulated study. In: Pre-failure deformation characteristics of geomaterials, pp 653–658

Mamatha KH, Dinesh SV (2018) Evaluation of strain modulus and deformation characteristics of geosynthetic-reinforced soil–aggregate system under repetitive loading. Int J Geotech Eng 12(6):546–555

Minažek K, Mulabdić M (2013) Pregled ispitivanja interakcije tla i armature u armiranom tlu pokusom izvlačenja. Građevinar 65(3):235–250

Puri P, Singh P, Garg P (2017) Effect of Sand on Strain Modulus (Ev2) Property of Clayey Soil

Réseau ferré de France (2010) Référentiel technique LGV dans le cadre de PPP ou de DSP tome 2—ouvrages en terre [Technical Reference LGV under PPP or DSP Volume 2—Earthworks]. Réseau ferré de France, Saint Denis, France, p 76 (in French)

Shin EC, Kim DH, Das BM (2002) Geogrid-reinforced railroad bed settlement due to cyclic load. Geotech Geol Eng 20(3):261–271

UIC (2008) UIC Code 719 R—Earthworks and track-bed for railway lines code. UIC, Paris, France, p 117