Effect of Track Speed on the Behavior of Railway Track Ballast System underlain by Clay

Mohammed Y. Fattah(1) Mahmood R. Mahmood(2) Mohammed F. Aswad(3)

(1) Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq. Email: myf_1968@yahoo.com.
(2) Assistant Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq. Email: 40083@uotechnology.edu.iq
(3) Assistant Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq. Email: 40083@uotechnology.edu.iq

Abstract
Railway ballast forms a major component of a conventional rail track and is used to distribute the load to the subgrade, providing a smooth running surface for the train. Currently, high speed (frequency) and heavy haul trains are increasing the loads experienced by the ballast layer.

In this paper a full scale railway system is analyzed numerically with finite element method using PLAXS 3D 2013 program. A series of 16 cases simulations for railway track of geometry type (MG) are analyzed. The analysis was performed in order to determine the effects of track speed, clay stiffness and reinforcement on the rail substructure behavior. Each model was analyzed for train speed 30, 60, 90, 120 km/hr., with and without geogrid reinforcement in the ballast layer for comparison. During the simulation, displacements and stresses were evaluated throughout the rail substructure in order to determine the behavior and improvement due to geogrid reinforcement.

It was concluded that the improvement in settlement for soft clay model increases by increasing the speed more than 30 km/hr. For unreinforced models with soft clay layer, at low speed (30 km/hr), about 100% of the total settlement appears in the clay layer. For stiff clay layer model, there is no effect of reinforcement on the behavior of settlement.

Key words: Railway, geogrid, clay, ballast, finite elements, track speed.

1. Introduction
Railways are one of the major modes of transportation around the world. In the recent years, owing to the increased number of rail commuters, railways face the challenge of increasing the competitiveness and attractiveness of rail transport in terms of speed (reduced travel time), increased tonnages, higher frequency of trains, availability and reliability with promising passenger comfort and safety. This in turn necessitates better quality of track that depends upon the better functioning of ballast, (Hussaini, 2013). It is well recognized that the engineering behavior of ballast is an Important parameter governing the stability
and performance of a given railway track structure (Trevizo, 1991; Selig and Waters, 1994).

Railroad foundations are geotechnical structures that are highly dependent on quality of ballast to dampen impact loading and railway vibration, facilitate easy construction, distribute stresses more evenly, reduce long-term settlements and provide a competent base under low confining pressures.

Leshchinsky and Ling (2013), investigated based on numerical modeling the effects of geocell confinement on ballasted embankments when encountering a soft subgrade, weaker ballast, or varying reinforcement stiffness’s, they concluded that the confinement of the ballast using geocell was quite effective in reducing vertical deformations, especially when low-quality material was used. Higher shear strength of the ballast reduces the need for reinforcement, reducing the need for substructure improvement. The use of geocell confinement reduced the vertical settlement, although it was not as significant as expected. The geocell allowed for a more uniform subgrade stress distribution.

Fattah et al. (2018), conducted laboratory tests to investigate the effect of load amplitude, load frequency, on the behavior of reinforced and unreinforced ballast layer. A half full-scale railway was constructed for carrying out the tests, which consists of two rails 800 mm in length with three wooden sleepers (900 mm × 90 mm × 90 mm). The ballast was overlying 500 mm thickness clay. The tests were carried out with and without geogrid reinforcement; the tests were carried out in a well tied steel box of 1.5 m length × 1 m width × 1 m height. A series of laboratory tests were conducted to investigate the response of the ballast and the clay layers where the ballast was reinforced by a geogrid. Settlement in ballast and clay was measured in reinforced and unreinforced ballast cases. They concluded that increasing the ballast layer thickness from 20 cm to 30 cm leads to decrease the settlement by about 50%. This ascertains the efficiency of ballast in spreading the waves induced by the track. The effect of load frequency on the settlement ratio is almost constant after 500 cycles.

Fattah et al. (2019), carried out a laboratory tests to study the effect of load amplitude, geogrid position, and number of geogrid layers, thickness of ballast layer and clay stiffness on the behavior of the reinforced ballast layer and induced strains in a geogrid. It was found that the amount of settlement increased as the simulated train load amplitude increased, and there was a sharp increase in settlement up to cycle 500. There was a slight increase in the induced settlement when the load amplitude increased from 0.5 to 1 ton but it was higher when the load amplitude increased to 2 tons. The position of the geogrid had no significant effect on the transmitted stresses. The value of the soil pressure and pore water pressure on ballast thicknesses of 20 cm was higher than for 30 cm and 40 cm thicknesses.

The objectives of the present study is to carry out numerical analysis to investigate the effect of track speed, stiffness of the clay subgrade layer and reinforcement of the subbase layer on the rail substructure behavior.
2. Railway Substructure Geometry
The standard railway substructure geometry type (GM) was formed a basis for the parametric study. The rail had height and base of 17cm and 15cm, respectively. The sleepers used in simulation are made of concrete, with a length of 2.5 m, a height of 0.17 m and 0.2 m width. They were spaced at 0.65 m on center.

The ballast embankment is 4.8 m width at the base, 3.0 m at the crest, and 0.3 m in height. The slopes have an inclination of 2:1 as specified by various rail design manuals (Leshchinsky and Ling, 2013). The geogrid would have to be placed in the ballast layer at a distance of 10 cm above the clay layer surface.

The length of the model for X and Y direction is 15 and 3.5 meters, respectively. The model depth of 5 m has been used which is considered appropriate where Feng, (2011) concluded that, "It is obvious that the size of the trackbed does not affect the dynamic property of the railway track model". Standard fixities and absorbent boundaries were applied in the model to reduce wave reflection at the boundaries to avoid any possible fictitious ground wave reflections.

3. Material Models and Properties
The ballast is assumed to follow as Mohr-Columb failure criteria. The rail and sleepers were modeled as linear elastic as non-yielding behavior is expected for sleepers and rails and a high magnitude of stiffness of these materials is assumed in comparison to those of the ballast. Clayey soil is modeled as a hardening undrained soil without considering any time-dependent behavior, such as consolidation. The geogrid was modeled as an elastic material. Table 1 summarizes the material properties used in the analysis.

| Parameter                          | Clay                  | Ballast               | Sleeper (concrete) | Rail (steel) |
|------------------------------------|-----------------------|-----------------------|--------------------|--------------|
| Material model                     | Hardening soil        | Mohr-Coulomb          | Linear elastic     |              |
| Drainage type                      | Undrained             | Drained               |                    |              |
| Unit weight, kN/m$^3$              | 18                    | 17.6                  | 20                 | 78.5         |
| Modulus of elasticity, kN/m$^2$    |                       | 200×10$^4$            | 30×10$^6$          | 210×10$^6$   |
| Cohesion $S_u$, $c$                | 25                    | 1                     | -                  | -            |
| Friction angle, $\phi$            | 0                     | 45$^\circ$            | -                  | -            |
| Dilatancy angle, $\psi$           | 0                     | 10                    | -                  | -            |
| Poisson's ratio, $\nu$            | 0.449                 | 0.25                  | 0.2                | 0.28         |
| $e_{initial}$                     | 0.61                  | 0.5                   | 0.5                | 0.5          |
| Compression index, $C_c$          | 0.18                  | -                     | -                  | -            |
| Swelling index, $C_s$             | 0.1                   | -                     | -                  | -            |
| Geogrid normal elastic stiffness $EA$ kN/m | 12000               |                      |                    |              |
4. Finite Element Mesh and Boundary Conditions

A full scale model with five sleepers cross section of rail track was adopted in presenting this analysis, because that, "when a wheel is centered over a sleeper, the sleeper directly beneath the load will generally carry less than half of that wheel load, with the remainder supported by two ties on either side", Figure 1 (Rail Road Design and Rehabilitation, 2000).

The vertical planes under the outer edge of the foundation are constrained from lateral displacement in the y-direction. The base of the model is restricted from any displacements.

The ballast is freely displaced in x and z direction, while a little displacement in the y direction (plane strain) was allowed to insure the geogrid strain in this direction. PLAXIS 3D 2013 software is used in the analysis. Figure 2 shows the finite element mesh.

![Figure 1: Load distribution along the track (Rail Road Design and Rehabilitation, US Army Corps of Engineers, 2000).](image)

![Figure 2: Finite element mesh.](image)
5. Loading
In order to demonstrate track loading behavior, a wagon was chosen for the analysis with four axles, each axle has a load of 25 tons. Therefore, a load of 12.5 tons placed on steel railroad track to represent point-loading of a wheel on a rail. The distances details of the wagon are shown in Figure 3. The loading was applied dynamically above the central sleeper. The time of dynamic load that was used in the program was representing 40 wagon passages which were calculated for each speed. The dynamic load multiplier was calculated for each speed to represent the well loading. Figures 4 to 7 show the load multiplier with time relationship for one wagon period of the speeds used in the analysis.

Figure 3: Wagon distances, (ARTC, 2016).

Figure 4: Load multiplier with time relationship for one wagon at 120 km/hr speed.

Figure 5: Load multiplier with time relationship for one wagon at 90 km/hr speed.
6. Results and Discussion

6.1 Displacements

Figures 8 to 11 show the settlement versus passing time relationship for the speeds 30, 60, 90 and 120 km/hr with stiff clay layer, soft clay layer in case of unreinforced and reinforced ballast layer.

From figures, it can be seen that the total settlement for the rail track for soft and stiff clay layers with reinforced ballast layer is lower than that of unreinforced layer, but the reduction in stiff clay model is very little.

Figure 12 presents the percentage of improvement in settlement of reinforced ballast layer in contrast with the unreinforced for deferent speeds, where:

\[
\% \text{ improvement} = \frac{\text{settlement of unreinforced ballast} - \text{settlement of reinforced ballast}}{\text{settlement of unreinforced ballast}} \quad \ldots \ldots (1)
\]

The figure illustrates that, for soft clay layer, the percentage of improvement at 30 km/hr. speed is about 9 %. The improvement increases by increasing the speed more than 30 km/hr, where the improvement is approximately leveled out at 90 km/hr speed and more at about 13 % improvement, on the other hand for stiff clay, the improvement was constant at all speeds which is about 6 %.
Figure 8: Settlement versus passing time relationship for the track model under the motion of train at 30 km/hr speed.

Figure 9: Settlement versus passing time relationship for the track model under the motion of train at 60 km/hr speed.

Figure 10: Settlement versus passing time relationship for the track model under the motion of train at 90 km/hr speed.
Figure 11: Settlement versus passing time relationship for track model under the motion of train at 120 km/hr speed.

Figure 12: Percent of improvement in settlement versus speed.

Figures 13 to 16 illustrate the percentage of settlement for the clay layer alone and the ballast layer alone compared to the total settlement of the model. For soft clay layer models, Figure 13 shows that at low speed (30 km/hr), about 100% of the total settlement appears in the clay layer, after this speed, the percentage of settlement is level out at about 80% in the clay layer and 20% in the ballast layer.

As seen in Figure 14, the effect of reinforcement on the behavior of soft clay is clear, it can be observed that the percentage of settlement for clay layer is about 80% and equal at all the speeds, as in ballast, the settlement percentage of soft ballast layer is about 20%.

For stiff clay layer models, there is no effect of reinforcement on the percentage of settlement or behavior of settlement as seen in Figures 15 and 16. That for both reinforced and unreinforced models, the settlement percentage is about 70% for clay layer, and about 0% for ballast layer at 30 km/hr speed, as the settlement percentage will remain constant at about 0% for clay layer and 20% for ballast layer for speeds 60 km/hr and more.
Figure 13: Percentage of settlement for the clay layer and ballast layer as a percent of the total settlement for soft clay and unreinforced ballast layers.

Figure 14: Percentage of settlement for the clay layer and ballast layer as a percent of the total settlement for soft clay and reinforced ballast layers.

Figure 15: Percentage of settlement for the clay layer and ballast layer as a percent of the total settlement for stiff clay and unreinforced ballast layers.
Conclusions:
1. The total settlement for the rail track for soft and stiff clay layers with reinforced ballast layer is lower than that of unreinforced layer, but the reduction in stiff clay model is very little.
2. For soft clay layer, the percentage of improvement in settlement at 30 km/hr. speed is about 9 %. The improvement increases by increasing the speed more than 30 km/hr, where the improvement is approximately leveled out at 90 km/hr speed and more at about 13 % improvement.
3. At low speed (30 km/hr), about 100 % of the total settlement appears in the clay layer, after this speed, the percentage in settlement is level out at about 80 % at clay layer and 20 % at ballast layer.
4. For both reinforced and unreinforced models, the settlement percentage is about 95 % for clay layer and about 5 % for ballast layer at 30 km/hr speed, as the settlement percentage will be level out at about 80 % for clay layer and 20 % for ballast layer for speeds 60 km/hr and more.

References
- Aswad M. F. (2016), "Behavior of improved railway ballast overlying clay using geogrid", Ph.D. thesis, Building and Construction Engineering Department, Unuiversity of Technology, Iraq.
- Hussaini S.K.K., (2013), ”An experimental study on the deformation behavior of geosynthetically reinforced ballast”, Ph.D. Thesis, University of Wollongong, Australia.
- Fattah M.Y., Mahmood M. R. and Aswad M.F, (2018),” Experimental and numerical behavior of railway track over geogrid reinforced ballast underlain by soft clay”, Proceedings of the 1st GeoMEast International Congress and Exhibition, Egypt 2017 on Sustainable Civil Infrastructures, Volume 14, p.p. 1-26.
• Fattah M.Y., Mahmood M. R. and Aswad M.F, (2019),” Stress distribution from railway track over geogrid reinforced ballast underlain by clay”, Earthquake Engineering and Engineering Vibration, Vol. 18, No.1, p.p. 77-93.

• Feng H. (2011), "3D-models of railway track for dynamic analysis", M.Sc. Thesis, Division of Highway and Railway Engineering, Department of Transport Science, School of Architecture and the Built Environment, Royal Institute of Technology, Stockholm.

• Leshchinsky B., Ling H. I., (2013) "Numerical modeling of behavior of railway ballasted structure with geocell Confinement", Geotextiles and Geomembranes, 36 (2013), p.p. 33-43.

• Rail Road Design and Rehabilitation, (2000), Technical Instruction, TI 850-20, Air Force AFMAN, US Army Corps of Engineering.

• Selig E.T. and Waters J.M. (1994), "Track Geotechnology and Substructure Management", 1st Ed., Technology Development and Application Committee, on behalf of the Railways of Australia.

• Trevizo, C. (1991). FAST/HAL Ballast experiment, Paper 16, AAR, Transp. Test Center-Pueblo, Colorado, p.p 9.