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ANALYSIS OF BALLASTLESS RAILWAY TRACK STRUCTURES OVER SOFT CLAYS

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Abstract: Railway developments in Egypt have gained much interest recently. This development was in many fields one of which is railway speeds and the term high speed trains "HST" was introduced as an alternative on Egyptian national railways. HST has many challenges from a geodynamic perspective; such as the case of HST operating in areas with soft soils such as soft clays in Delta area in Egypt. In this paper, the problem of HST over soft soils was considered from a dynamic response point of view and ballastless tracks was investigated and compared with the traditional ballasted track. A track concept was introduced recently as a solution for this problem called "Deck track" but very few literature studied this idea. This track concept was studied and further modified into two other types. These tracks were dynamically analyzed using 3D finite element modeling constructed. Results of the ballastless track models will be compared with the Ballasted track model in order to observe if it mitigates the effects of HST over soft clays or not and also to show if the modified tracks is performing better than the Deck track or not. Dynamic response results of the models were displayed and comparisons were made for all track structures.

Keywords: *Deck track, railway on soft soil, finite element model, ballastless track.*

1.0 Introduction

Recently Egypt had a growing interest in developing the Railways. In the last 40 years an increase in train speed and axle load around the world. High speed trains (HST) has developed rapidly and gained much interest due to its impact on the economy of a country (Esveld, 2001). HST has many challenges from a geodynamic point of view (Madshus *et al*., 2004), these challenges gave birth to ballastless railway track system (slab track) and almost all HST developed by any country was associated with a similar development in the structure of railway tracks supporting this HST (Esveld, 2001). One of these HST challenges was the critical speed that any train must not reach (Madshus *et al*., 2001); this critical speed was the result of a structural behavior called Resonance that will occur between the frequency the HST propagates and either the natural frequency of the superstructure itself or the shear wave velocity of the substructure (Madshus *et al*., 2001). The problem of resonance with the superstructure can be easily avoided by increasing the bending stiffness of the superstructure via Slab track approach; the problem of the substructure on the other hand is much more complicated and costly. This substructure problem happens when the supporting soil beneath the track is considered a weak soil such as soft clays (Woldringh *et al*., 1999). The soft clays and very soft clays has relatively low shear wave velocity that can get as low as 60 m/s (216 kph), this low shear wave velocity makes the situation of resonance occurrence a very likely to happen scenario. Once the train reaches the critical velocity, large displacements can be observed (Adolfsson *et al*., 1999) and much more seriously, Mach cones like ones that flying jets produce in the air can form inside the clay soil beneath the track (Peter *et al*., 2013) which produces severe displacements that can damage the structure in this zone. Another problem associated with soft clays is consolidation settlement that can easily make structural damages to HST (Dingqing *et al*., 2015).

Several classical attempts have been made from a geotechnical point of view to overcome this problem. Some commonly used improvement techniques are vibro replacement techniques, deep soil mixing techniques, jet grouting and soil removal and replacement techniques (Dingqing *et al*., 2015). Another very recent approach was the Deck track concept (Bos, 2000 and Ismail, 2016). The concept is based on a reinforced concrete supporting body with a hollow shape. Its weight is less than that of the soil excavated for its laying. Almost no consolidation settlement will occur as a result of the weight of the structure (Bos, 2000), (Ismail, 2016). This type of structure solves both the problem of the low bending stiffness of the track and the problem of soil weakness underneath. Yet, almost no researches have been made to further study and analyze this track and no literature is built in that field. This contribution is to add to the literature and the study of this new track idea. To conduct this analysis, a comparison study is made between traditional ballasted tracks over soft clays, new Deck track concept and new modified tracks suggested in the study called the Inverted Deck track and Curved Deck track. The analysis was conducted using ABAQUS FEA (ABAQUS, 2000) software by building 3-D models representing the four structure types and studying their dynamic response over a moving load unit. Then results of the analysis were compared and observations on the best dynamic behavior were discussed.

2.0 Finite Element Modelling

The four track models were set to 70 m in length. This was assumed as an initial estimate since only the response close to the track was considered; The three dimensional models, consisted of rails of UIC60 (International Union of railways standard rails), concrete mono block sleepers with dimensions (2.8, 0.28 and 0.2m) and are equally spaced in a 0.5 m discrete sleepers, the ballasted track only had the following layers: ballast layer, subballast layer, Fill layer and the Soft Clay layer. Yet the other tracks, the deck track, inverted and the curved tracks consisted of the concrete track lying directly on the soft clay layer. Figure 1 generally shows the four models.

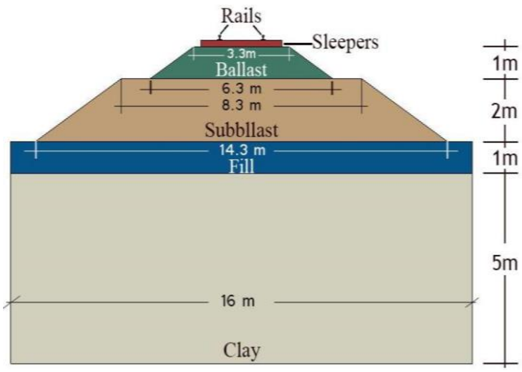
A fixed boundary was used in the bottom of the model. Infinite elements based on the previous work (Lysmer *et al*., 1969) are used on the X and Z direction boundaries to represent the infinite boundary condition to absorb Shear and Pressure waves and prevents reflections of these waves. The nodes at the bottom boundary were fixed in every direction to simulate bedrock. Both ends of the ground boundary were fixed in the out of plane direction in order to keep the ground in place at the ends of the finite element model. The elements used in the modeling are the 3D Linear Hexahedron element, C3D8R for all the elements except for the infinite elements which CIN3D8 Linear Hexahedron element is used (ABAQUS, 2000).

All materials used for the track and rail in this study were assumed to be linear elastic except for the clay which is modeled as an elastic perfectly-plastic material which forms a combination behavior between Hook‘s law and the general form of Mohr Coulomb‘s failure criterion (Mohamed, 2008). The material properties of each component are summarized in Table 1.

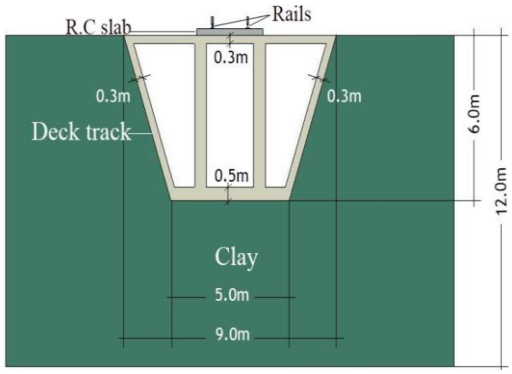
The loading is only considered a single bogie loading unit with a wheel load of 8 tons moving with four specific varying velocities of (100, 150, 200 and 250 kph) and The analysis type used to model the dynamic movement of the train loading unit is Dynamic Explicit Analysis in which is very suitable for detecting actions occurring within very short periods of time. The time period of the total analysis is calculated for each train speed model separately in order to allow the loading unit to reach from the beginning of the track structure all the way to the end of the 70 m track therefore four different time periods are given for each velocity The incrimination time is assumed automatic with a time scaling default factor of 1 for all of the ballasted tracks modeled.

The interaction between the wheels and the rails is assumed to be surface to surface contact and with tangential friction coefficient of zero in order to allow the wheel to move freely and it was not intended to study the friction between the wheel and the rail in this matter, the normal contact between the wheel and the rail is assumed to be in hard contact. Other contacts between (Rails and Sleepers, Sleepers and Ballast, Ballast and

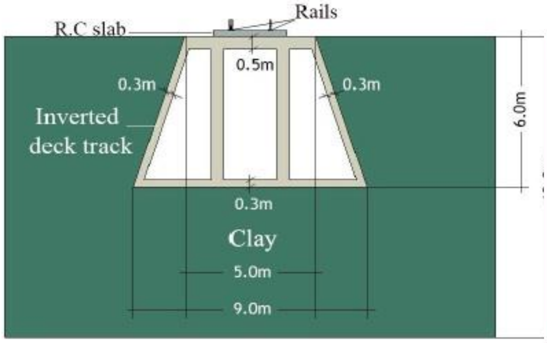
Sub ballast, Sub ballast and Fill, and Fill and Clay) are assumed to be in surface to surface tied contact since these layers are infinite and not assumed to be relatively shifting from one another.



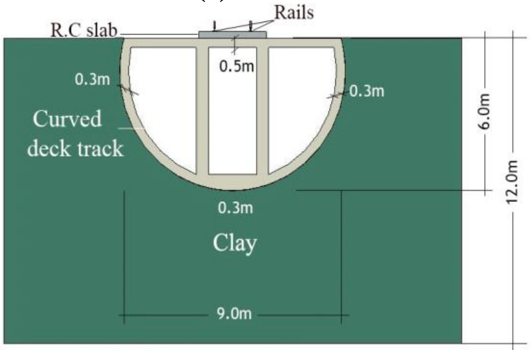
(a) Ballasted track



(b) Deck track



(c) Inverted Deck track



(d) Curved Deck track

Figure 1: Track models

Table 1: Ballasted track material properties

Component	*ρ (kg/m³)*	*E (MPa)*	*μ*	*C (kPa)*	*ϕ*	*V_s (m/s)*
Rail	7800	200000	0.3	-	-	3392
Sleeper	2500	25000	0.2	-	-	1826
Ballast	2200	200	0.2	-	-	261
Subballast	1800	150	0.2	-	-	230
Fill	1800	90	0.3	-	-	138
Clay	1600	25	0.35	8	20	75

Where, ρ is density, E is Young's Modulus, μ is Poisson's ratio, C is soil cohesion, ϕ is the angle of internal friction and $V_s$is shear wave velocity.

3.0 Finite Element Results

In order to investigate the dynamic characteristics of the four previously defined track structures (Traditional Ballasted Track, Deck Track, Inverted Deck Track and the Curved Deck Track), the Dynamic Responses in the form of time histories for the vertical displacements and vertical accelerations of these structures is to be displayed and compared. Special observation points were selected at specific places for the four structures as shown in Figure 2. OP.1 is intended to be at the top of the Rail Head, this observation point is important and gives a better understanding of the behavior in which the train will experience, so it is very important to see clearly the vertical displacements and the vertical accelerations at this observation point. OP.2 on the other hand is located at the main structure or the superstructure and its importance comes where it shows the displacements and the accelerations that the structure itself will experience, OP.3 and OP.4 is much more important specially in our study, that is because these points are located in the clay layer beneath the track and these points will show how the clay layer will behave at various velocities of trains on the three main structures studied. OP.3 is located at the very top of the clay layer to display the maximum dynamic effect that this layer will suffer from. OP.4 is located 2 meters below OP.3 and will show what the clay layer itself will experience during the dynamic loading of the train at various velocities.
Since it was difficult to display all the time history charts for all four structure at all the four observation points for the different four velocities, combined charts were considered with only the maximum lower displacements and the absolute maximum acceleration, these combined charts show the varying velocity on the x-axis and the dynamic response on the y-axis for any observation point.

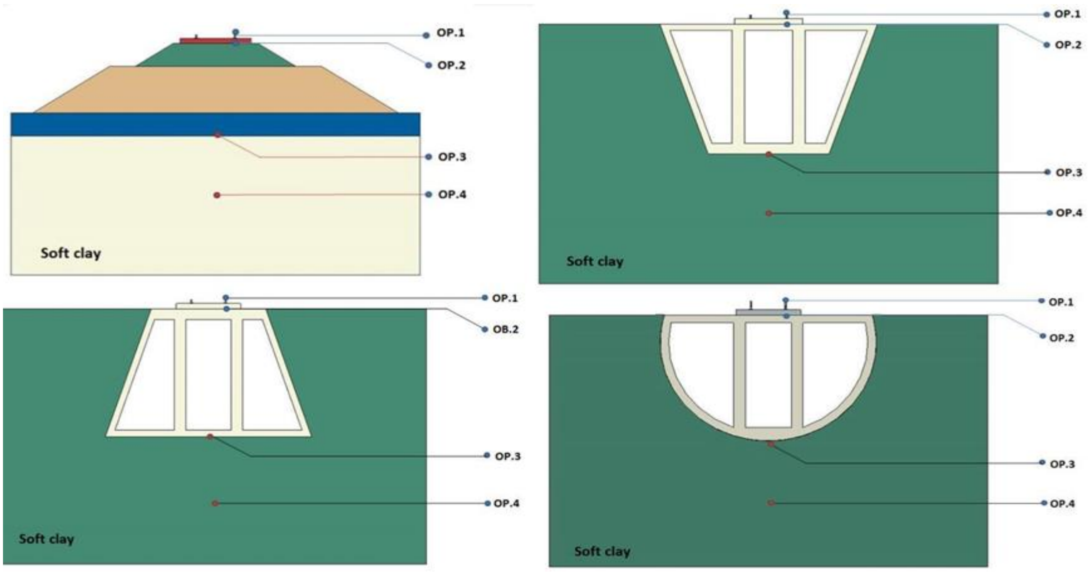
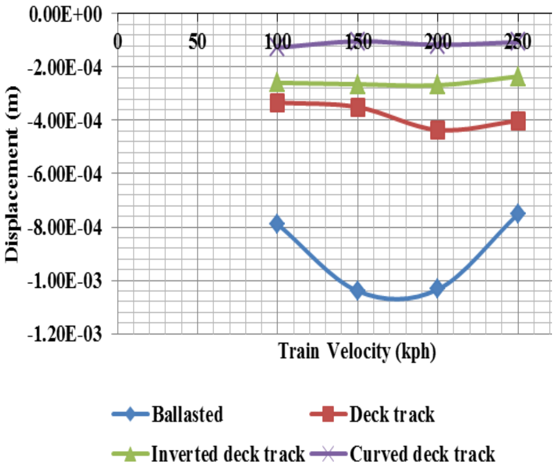


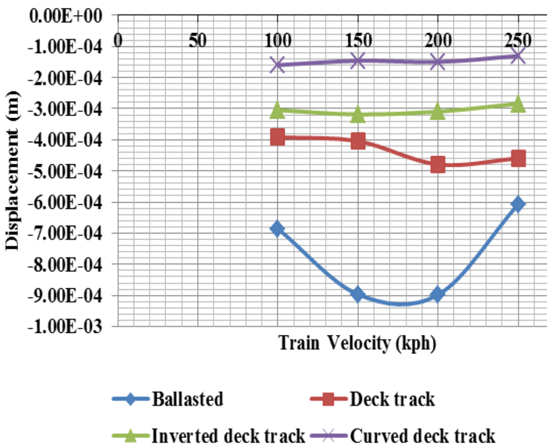
Figure 2: The observation points

3.1 Vertical Displacements

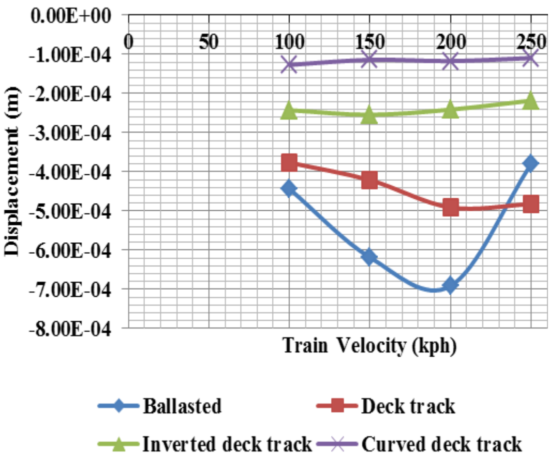
The following graphs represent the maximum vertical displacements in meters for the three track structures in the study at the observation points defined previously (OP1, OP2, OP3 and OP4) with varying train velocities of (100,150,200 and 250 kph).



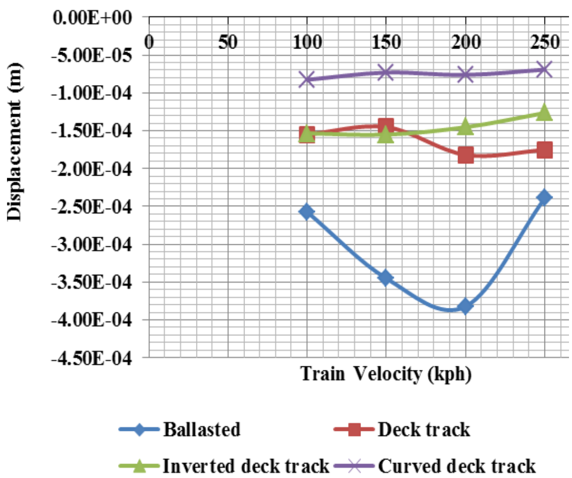
Combined Vertical Displacements at OP.1.



Combined Vertical Displacements at OP.2.



Combined Vertical Displacements at OP.3.



Combined Vertical Displacements at OP.4.

Figure 3: Combined Vertical Displacements at OP.1. , OP.2. , OP.3. & OP.4.

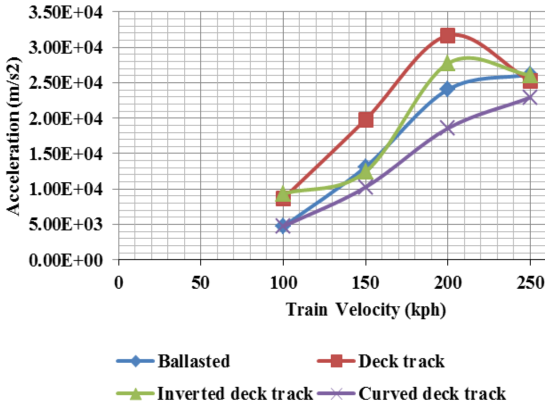
There is an obvious important observation that can be made when previously displayed charts is studied, this observation is that the Curved deck track and the Inverted Deck Track had the best dynamic responses among all three structures displayed, they had a significant advantage over the ballasted track concerning the maximum vertical displacements and specially for the superstructure part, the Curved deck track and the Inverted Deck track had a maximum displacements of less than ¼ of the Ballasted tracks maximum vertical displacements, also the Curved deck track showed an advantage over the Deck track structure specially at the superstructure.

Comparing the Inverted Deck track with the Deck track's behavior, at velocities of 100 through 150 kph the dynamic response of the Inverted Deck track was very much similar as the Deck track‘s response but as the velocity went higher and closer to a critical velocity condition the dynamic response behavior was getting very much in the Inverted Deck track‘s favor and the vertical displacement at 250 kph was ½ the value of the Deck Track‘s.

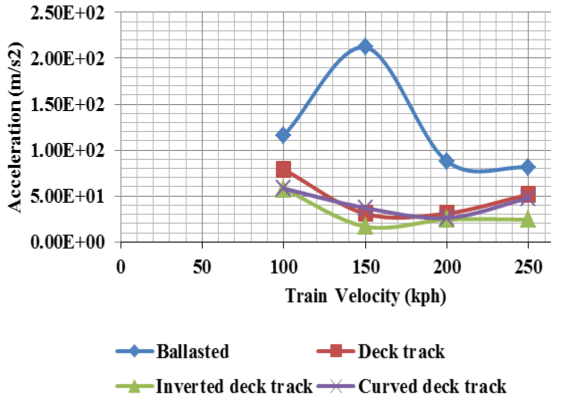
The soft clay layer is telling the same story but with a different scenario, the overall advantage was in the favor of the Curved deck track and the Inverted Deck track over the two other systems also we can notice that as the velocity goes to 250 kph the vertical displacement of the Ballasted track gets lower and almost equals the Deck track‘s value but yet still higher than the Curved deck track and the Inverted Deck track.

3.2 Vertical Acceleration

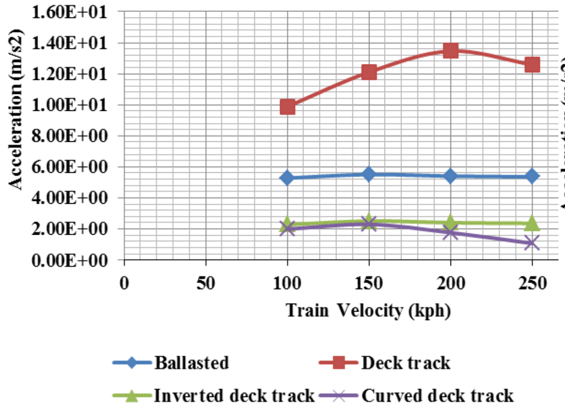
The following graphs represent the maximum vertical accelerations in m/s^2 for the three track structures in the study at the observation points defined previously (OP1, OP2, OP3 and OP4) with varying train velocities of (100,150,200 and 250 kph).



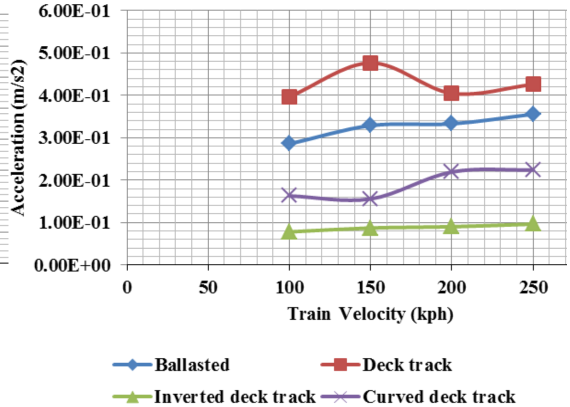
Combined Vertical accelerations at OP.1.



Combined Vertical accelerations at OP.2.



Combined Vertical accelerations at OP.3.



Combined Vertical accelerations at OP.4.

Figure 4: Combined Vertical accelerations at OP.1. , OP.2. , OP.3. & OP.4.

The first most obvious observation when we examine the previous charts is that we notice that the Deck track had overall the worst dynamic response of all the four structures analyzed even when compared with the traditional ballasted track specially at observation points 3 and 4 which indicates the acceleration transmitted into the clay layer.

Also, The previous charts show clearly the significance of the curved deck track and the Inverted Deck track over the other track structures, at the rail head “OP.1” it can be noticed that the three structure almost matched each other‘s behaviors and gave almost identical dynamic response, the maximum vertical acceleration gradually increased as the velocity increased. But the most important conclusion is clearly shown in the charts after that (OP.2, OP.3 and OP.4), these charts show the huge advantage of using the curved deck track and the Inverted Deck tracks for high speed trains on soft clays, relatively small dynamic response is shown indicating that specifically the Inverted Deck track structure had the ability to absorb the dynamic energy and distribute it along the whole track which minimized the effect of vertical accelerations in the soft clay layer compared with the other systems to the point where it was almost zero at the observation point OP.4 two meters below the superstructure.

4.0 Observations

The following tables show how the deck track and the inverted deck track and the curved deck track are relatively behaving over the traditional ballasted track. The ballasted track dynamic response data are assumed to be the basis of our observation and reduced values or increased values are calculated based upon them.

Table 2: Relative Vertical Displacements at OP.1

Velocity	Deck track	Inverted deck track	Curved deck track
100	Reduced by 57.79 %	Reduced by 67.24 %	Reduced by 83.93%
150	Reduced by 66.36 %	Reduced by 74.59 %	Reduced by 90.09%
200	Reduced by 57.85 %	Reduced by 74.08 %	Reduced by 88.74%
250	Reduced by 46.58 %	Reduced by 68.75 %	Reduced by 85.87%

Table 3: Relative Vertical Displacements at OP.2

Velocity	Deck track	Inverted deck track	Curved deck track
100	Reduced by 42.90 %	Reduced by 55.5 9 %	Reduced by 76.69%
150	Reduced by 54.91 %	Reduced by 64.51 %	Reduced by 83.75%
200	Reduced by 46.63 %	Reduced by 65.53 %	Reduced by 83.34%
250	Reduced by 24.24 %	Reduced by 53.23 %	Reduced by 78.50%

Table 4: Relative Vertical Displacements at OP.3

Velocity	Deck track	Inverted deck track	Curved deck track
100	Reduced by 15.19%	Reduced by 45.37%	Reduced by 71.42%
150	Reduced by 31.91%	Reduced by 58.91%	Reduced by 81.60%
200	Reduced by 28.98%	Reduced by 65.15%	Reduced by 83.06%
250	Increased by26.91%	Reduced by 42.63%	Reduced by 71.24%

Table 5: Relative Vertical Displacements at OP.4

Velocity	Deck track	Inverted deck track	Curved deck track
100	Reduced by 39.87 %	Reduced by 40.40 %	Reduced by 67.93%
150	Reduced by 57.95 %	Reduced by 55.07 %	Reduced by 78.85%
200	Reduced by 52.41 %	Reduced by 61.98 %	Reduced by 80.05%
250	Reduced by 26.60 %	Reduced by 47.09 %	Reduced by 71.08%

Table 6: Relative Vertical accelerations at OP.1

Velocity	Deck track	Inverted deck track	Curved deck track
100	Increased by84.16%	Increased by99.10%	Reduced by 0.74%
150	Increased by50.87%	Reduced by 5.25%	Increased by21.86%
200	Increased by31.75%	Increased by15.36%	Increased by22.75%
250	Reduced by 3.59%	Reduced by 0.49%	Increased by12.51%

Table 7: Relative Vertical accelerations at OP.2

Velocity	Deck track	Inverted deck track	Curved deck track
100	Reduced by 31.95%	Reduced by 50.21%5	Reduced by 49.79%
150	Reduced by 85.51%	Reduced by 92.09%	Reduced by 82.51%
200	Reduced by 64.58%	Reduced by 72.16%	Reduced by 70.21%
250	Reduced by 36.41%	Reduced by 70.13%	Reduced by 41.19%

Table 8: Relative Vertical accelerations at OP.3

Velocity	Deck track	Inverted deck track	Curved deck track
100	Increased by87.25%	Reduced by 56.85%	Reduced by 62.33%
150	Increased by119.58%	Reduced by 54.45%	Reduced by 58.27%
200	Increased by149.11%	Reduced by 55.52%	Reduced by 67.3%5
250	Increased by134.83%	Reduced by 55.96%	Reduced by 79.95%

Table 9: Relative Vertical accelerations at OP.4

Velocity	Deck track	Inverted deck track	Curved deck track
100	Increased by38.98 %	Reduced by 72.67 %	Reduced by 42.95%
150	Increased by44.97 %	Reduced by 73.46 %	Reduced by 52.58%
200	Increased by21.58 %	Reduced by 72.90 %	Reduced by 34.08%
250	Increased by19.74 %	Reduced by 72.90 %	Reduced by 36.95%

As noticed from the behavior of the three structures over the ballasted track we can observe that the deck track and the inverted and the curved tracks was very efficient dynamically when considering vertical displacements they significantly reduced the displacement values on all velocities. It is also noticed that as the velocity is getting higher than 200 kph the vertical displacements on the ballasted track is been reduced and the improvements done by the other structures are getting smaller which indicates that maybe for higher speeds than 250 kph the ballasted track may give similar results as the deck and the inverted and the curved. But as we consider the accelerations, a different scenario is occurring; we can notice the significance of the inverted and curved deck tracks over the ballasted track especially in the soft clay zone.

But as the improvements done by the deck track is compared, it can be noticed that it gave worse results than the traditional ballasted tracks, this may be due to the absorption mechanism of the soils used in ballasted tracks versus the stiff behavior of the deck structure itself and due to the small area of support of the deck track compared to the supporting area of the inverted and the curved deck tracks which acts as a magnifier to the accelerations occurring on the top part of the track as opposed to the inverted and the curved which lessen the effect of accelerations occurring at the top of the structure.

5.0 Conclusion

The purpose of this paper was to investigate and study the dynamic response of Ballastless railway tracks on soft soil under high speed trains (100 to 250 kph) based on three dimensional finite element methods. This investigation is conducted as a comparative study between traditional ballasted tracks and three other ballastless tracks “Deck track, Inverted deck track and curved deck track”, different models were created and dynamic response output data were compared. Conclusions about the results are presented as follows:

- When results of the Deck track is compared with ones of the ballasted track it was clearly noticed a reduction in the vertical displacements by an average percentage of 40% was achieved but from an acceleration point of view the results was in the favor of the Ballasted tracks specially in the soft clay layer.

- Inverted deck track was a modification on the original deck track concept which was based on the idea of making a broader supporting area which will help in dissipating the energy induced by the speeding trains.

- By comparing results of this track it showed a huge advantage over the ballasted and the Deck track and it was able to reduce the vertical displacements compared with the ballasted track by an average percentage of 60% and the acceleration was reduced by 40% on average which is far more great advantage over the Deck track's results also.

- Another modified track was considered "the Curved deck track" in the study in order to optimize the best track to sustain under high speed trains over soft clays, the compared results of this track showed great significance over the ballasted track and the vertical displacements were reduced by 80% on average and vertical accelerations were reduced by 35% on average which in this case not as good as the Inverted track. But overall, it can be considered the best behaving track that could sustain high speed trains over soft clay soils.

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