Malaysian Journal of Civil Engineering 29(3):239-249 (2017)

INVESTIGATION OF MACH CONE DEVELOPMENT IN BALLASTLESS RAILWAY TRACK STRUCTURES OVER SOFT CLAYS

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Abstract: High speed trains (HST) have many challenges from a geodynamic perspective; such as the case of HST operating in areas with soft soils like soft clays in Delta areas. The speeding trains can easily reach critical velocity due to the resonance of Rayleigh surface waves developed by the train and the low shear wave velocity of the soft soil. When this resonance happens it can develop a phenomenon called "Mach cones" which is similar to the ones the air jets produce at the speed of sound. This phenomenon can be observed in theoretical analytical measurements as well as in practical measurements. This paper studies the occurrence of mach cones in the soft clay soil under ballastless track structure systems and compares this phenomenon with the traditional ballasted track. Results of the displacement contours in the clay layer of the ballasted track show concentric pattern with train velocity of 250 km/h which indicated mach cone development around this velocity. Other ballastless track types modeled show that the displacement contours are distributed with no concentric pattern and indicating no mach cones even with velocities reaching 250 km/h.

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

1.0 Introduction

Recently Egypt had a growing interest in developing Railway lines. In the past 40 years there has been a significant increase in train speeds and axle loads around the world. High speed trains (HST) has developed rapidly and gained much interest due to its impact on the economy of countries (Esveld 2001). HST had 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*. 2000); this critical speed was the result of a structural behavior called Resonance that occur between the frequency which the HST propagates and either the natural frequency of the superstructure itself or the shear wave velocity of the substructure (Madshus *et al*. 2000). 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. The substructure problem appears when the supporting soil beneath the track is considered relatively 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 which produces severe displacements that can damage the structure in this zone, these mach cones can be analytically observed in a displacement contour diagram as a concentric pattern occurring just before and at the time of Mach cones occurrence (Peter *et al*. 2013).

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 & Ismail 2016). The concept is based on a reinforced concrete supporting body with a hollow shape with weight less than that of the soil excavated beneath, 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 this field. This contribution is to add to the literature and the study of this new track idea specially the occurrence of mach cones under three ballastless track types and for the traditional ballasted track. To conduct this analysis, a visual comparison study is to be made between traditional ballasted track over soft clays, new Deck track concept and new modified track suggested in the study called the Inverted Deck track and Curved Deck track in order to observe the occurrence of a concentric pattern in the contour diagram under the train loads which indicate a mach cone situation. The analysis is done using ABAQUS FEA software by building 3-D models representing the four structure types and studying their dynamic response over a moving load unit representing the train.

2.0 Finite Element Modeling

The 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, concrete mono block sleepers with dimensions (2.8, 0.28

and 0.2m) and are equally spaced in a 0.5m discrete sleepers, the ballasted track only had the following layers: ballast layer, sub ballast 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 & Kuhlemeyer 1969) are used on the side 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 (Hibbit & Karlsson 2000).

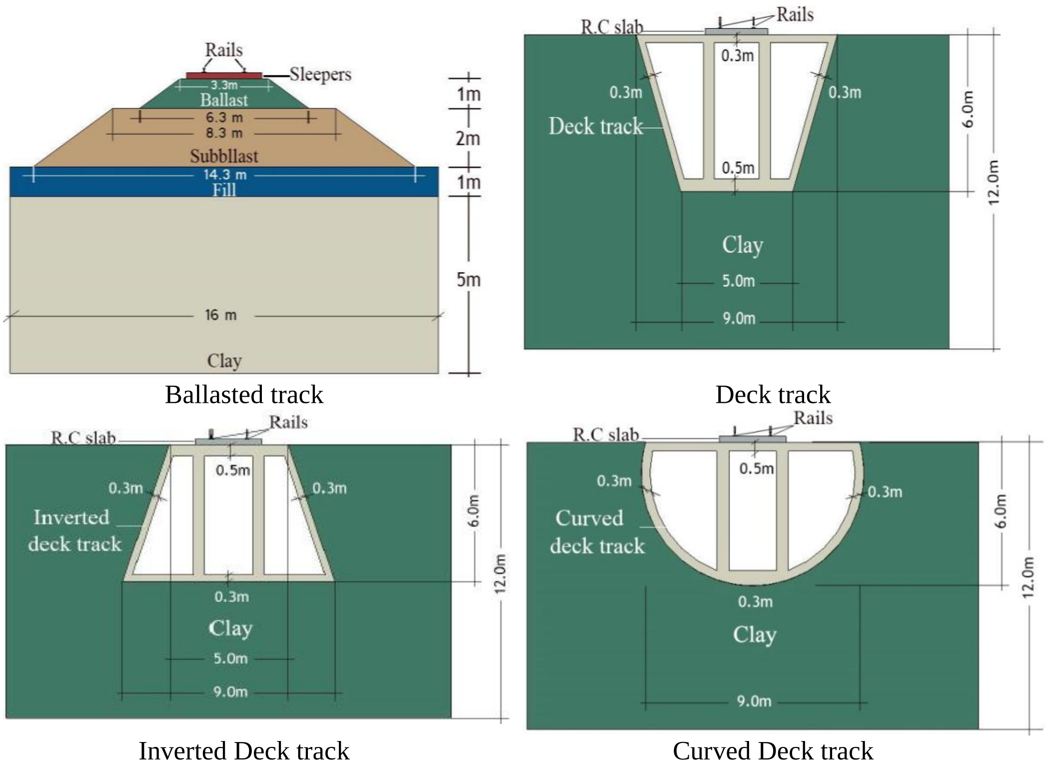

Figure 1: Track models.

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 this clay behaviour was suggested by Shahin (2008) which he compared different clay models and compared the results to indicate which model gave more accurate results. The material properties of each component are summarized in Table 1.

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
Sub ballast	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.

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 km/h) and The analysis type used is Dynamic Explicit Analysis. 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 70m 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 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.

3.0 Finite Element Results

In order to investigate the occurrence of Mach cones for the four track structures (Traditional Ballasted Track, Deck Track, Inverted Deck Track and the Curved Deck Track), Visual displacement contour results will be displayed to show if a concentric pattern happening or not which can be indicating a mach cone development.

3.1 Ballasted track

Figures 1 till 5 show the vertical displacements contour diagrams in the clay layer in order to spot whether a mach cone concentric pattern will tend to form on higher velocity or not. The section of observation is taken just below the fill layer at the upper part of the clay which will show the displacement contour patterns better than if deeper sections were taken.

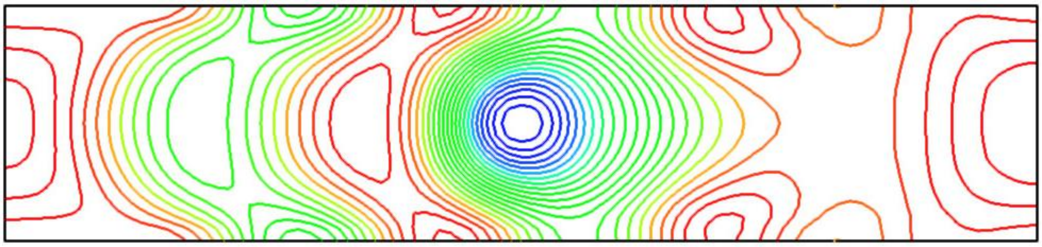

Figure 2: Ballasted track displacement contour diagram at velocity = 100 km/h.

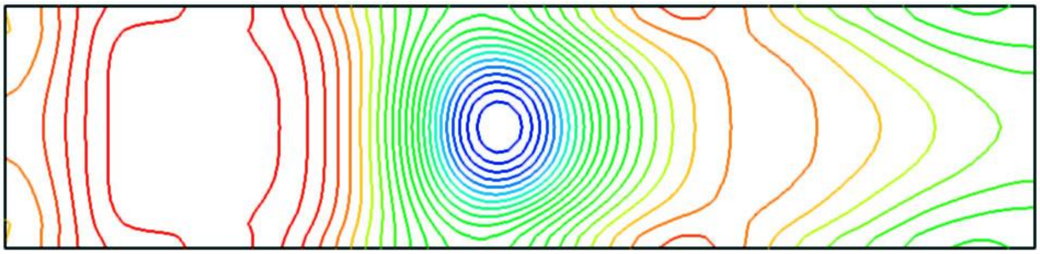

Figure 3: Ballasted track displacement contour diagram at velocity = 150 km/h.

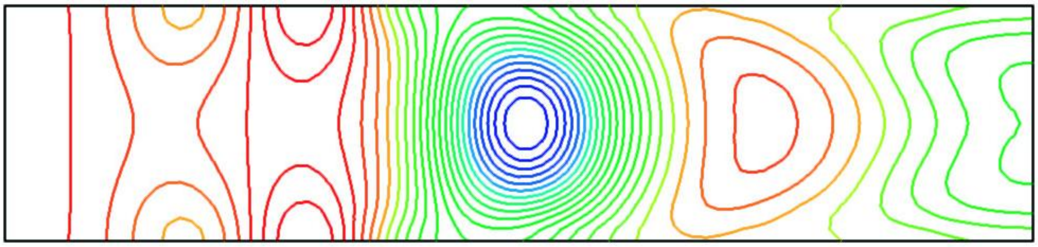

Figure 4: Ballasted track displacement contour diagram at velocity = 200 km/h.

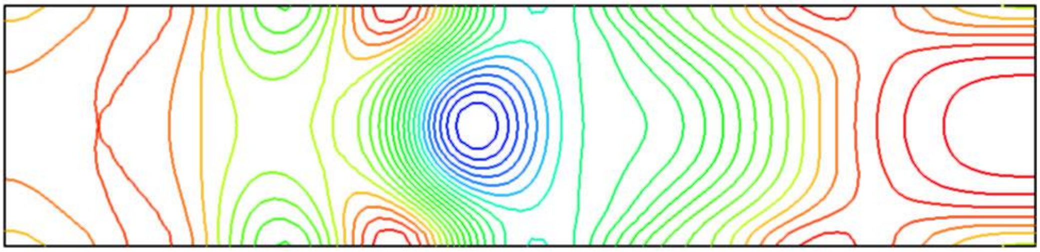

Figure 5: Ballasted track displacement contour diagram at velocity = 250 km/h.

3.2 *Deck track*

Figures 6 till 9 also show the vertical displacements contour diagrams in the clay layer beneath the deck track to observe the contour pattern. The deck track structure is hidden from the results and the clay part is exposed in order to observe the displacement contours on top of the clay layer just beneath the track structure.

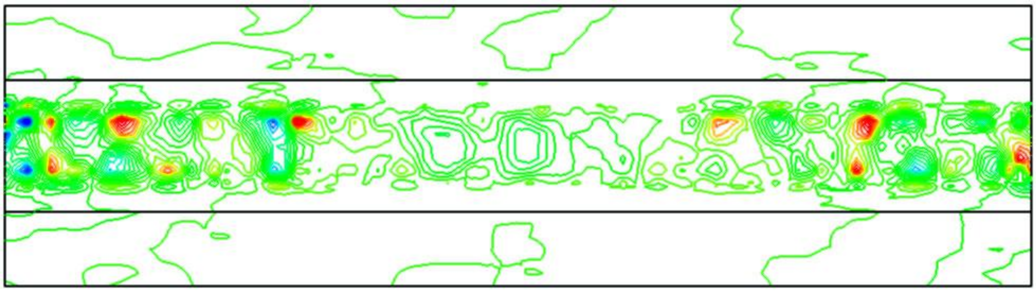

Figure 6: Deck track displacement contour diagram at velocity = 100 km/h.

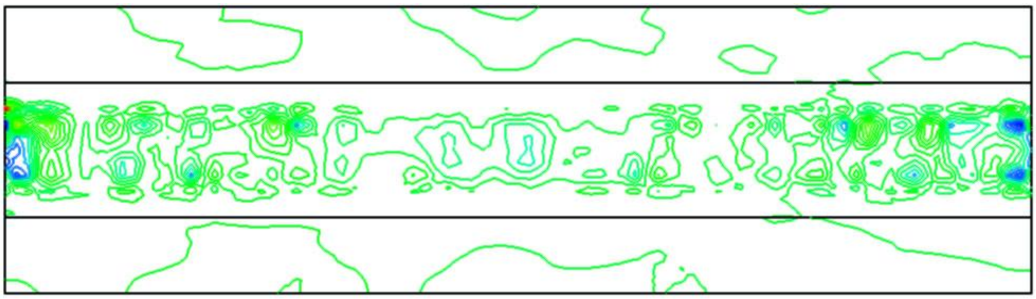

Figure 7: Deck track displacement contour diagram at velocity = 150 km/h.

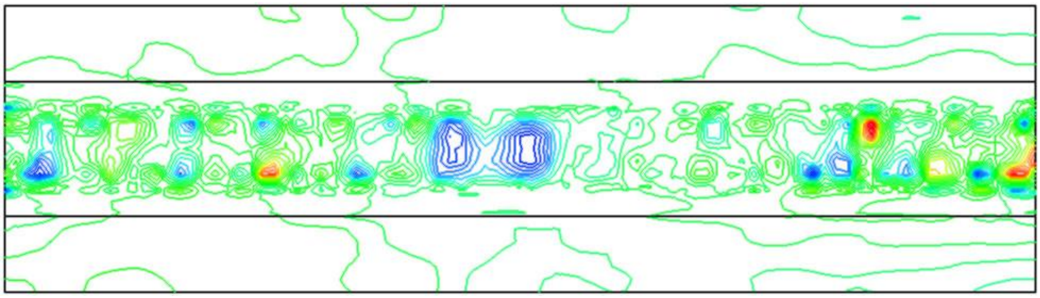

Figure 8: Deck track displacement contour diagram at velocity = 200 km/h.

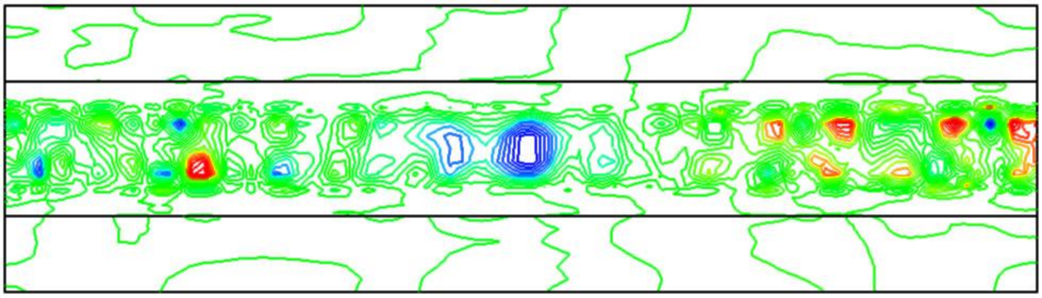

Figure 9: Deck track displacement contour diagram at velocity = 250 km/h.

3.3 Inverted Deck track

Figures 10 till 13 also show the vertical displacements contour diagrams in the clay layer beneath the inverted deck track to observe the contour pattern. The inverted deck track structure is hidden from the results and the clay part is exposed in order to observe the displacement contours on top of the clay layer just beneath the track structure.

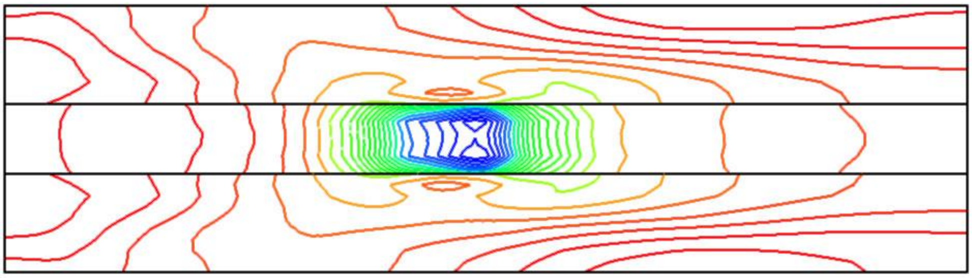

Figure 10: Inverted deck track displacement contour diagram at velocity = 100 km/h.

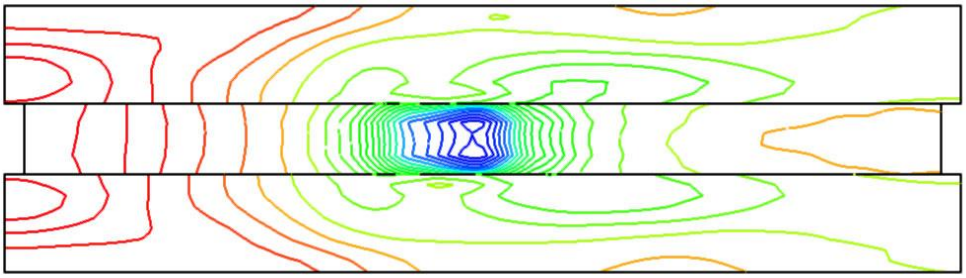

Figure 11: Inverted deck track displacement contour diagram at velocity = 150 km/h.

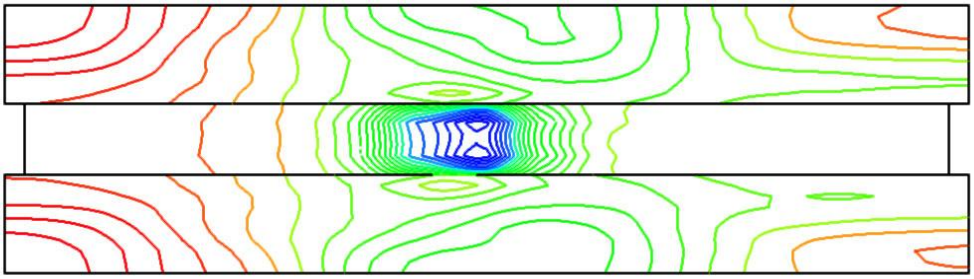

Figure 12: Inverted deck track displacement contour diagram at velocity = 200 km/h.

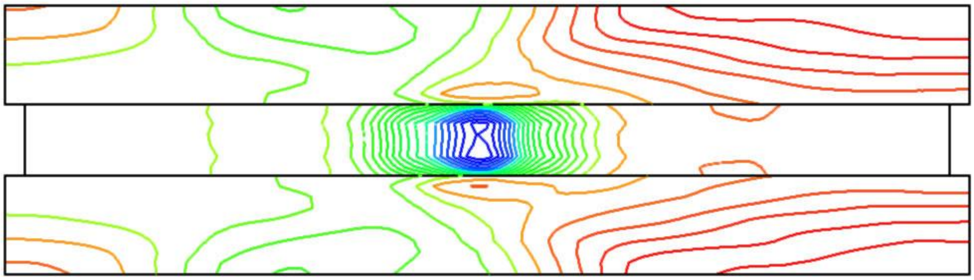

Figure 13: Inverted deck track displacement contour diagram at velocity = 250 km/h.

3.4 Curved Deck track

Figures 14 to 17 also show the vertical displacements contour diagrams in the clay layer beneath the inverted deck track to observe the contour pattern. The curved deck track structure is hidden from the results and the clay part is exposed in order to observe the displacement contours on top of the clay layer just beneath the track structure.

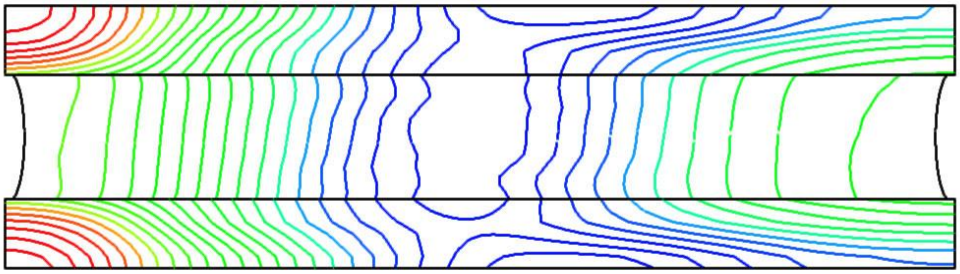

Figure 14: Curved deck track displacement contour diagram at velocity = 100 km/h.

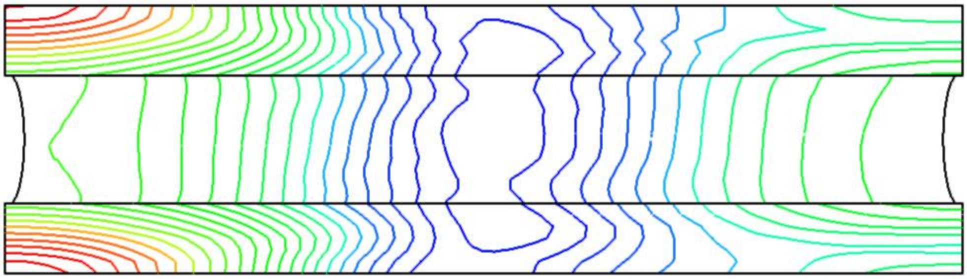

Figure 15: Curved deck track displacement contour diagram at velocity = 150 km/h.

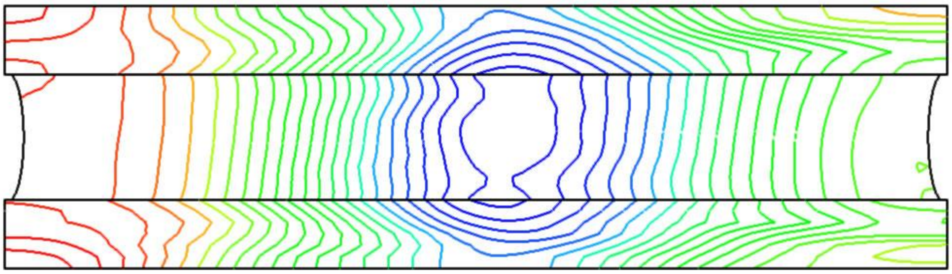

Figure 16: Curved deck track displacement contour diagram at velocity = 200 km/h.

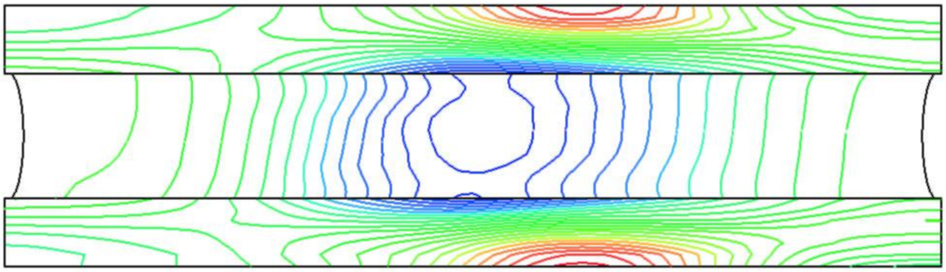

Figure 17: Curved deck track displacement contour diagram at velocity = 250 km/h.

4.0 Discussion

From the previously displayed diagrams we can observe that the ballasted track was a good load displacement conductor and we can clearly locate the position of the train even meters below the track, this can be due to the low bending stiffness of the track that allows the load leave a strong print inside the clay layer. The contour diagrams at the ballasted track was almost homogeneously circular at velocities of 100, 150 and 200 km/h but when the velocity reached 250 km/h a slightly observed concentric pattern is visible and tends to show strain energy concentration ahead of the loads which indicate that a mach cone is about to occur or might occurred in a velocity between 200 and 250 km/h. On the other hand, for the rest of the concrete hollow tracks “deck track, inverted deck track and curved deck track” we can observe a high distribution of displacement in the clay layer and the load is becoming less observable compared to the ballasted track one. This observation can be due to the high bending stiffness of the track. But it is also observed that the curved deck track was the best of the tracks in distributing the displacement beneath the track this can be observed as the displacement contours were far apart compared with other tracks contours which indicate a smoother displacement distribution, this can be due to the good load distribution along the curved surface.

5.0 Conclusion

The purpose of this paper was to investigate the development of mach cones in Ballastless railway tracks on soft soil under high speed trains (100 to 250 km/h) 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:

- Traditional ballasted tracks on soft clay can easily develop mach cones in the soft clay with velocities approaching 200 km/h which gives us a recommendation not to exceed this velocity if a traditional ballasted track is built in Egypt to serve a HST line specially in Delta and east Port Said areas.

- Ballastless railway tracks and specially deck, inverted deck and curved deck tracks can sustain HST without developing mach cone effects in the soft clay layer due to their high bending stiffness.

- Curved deck track has the best performance relative to the other three tracks investigated in distributing the load and protecting the soft clay layer from mach cones, this is due to the good surface to surface distribution of loads along the curved section.

References

Adolfsson K., Andreasson B., and Zakrisson P. (1999). *High Speed Train X2000 on Soft Organic Clay-Measurements In Sweden*. 12th European Conf. of Soil Mech. and Geot. Eng. Amsterdam.

Bos J. (2000). *Deck Track: Foundation for the Railways of the Future*. Holland Railconsult.

Dingqing L., James H., and Chrismer S. (2015). *Railway Geotechnics*. ISBN: 9780415695015, CRC Press.

El Kacimi A., Woodward P. K., Laghrouche O., and Medero G. (2013). *Time domain 3D finite element modelling of train-induced vibration at high speed*, Computers and Structures, vol. 118, pp. 66–73.

Esveld C. (2001). *Modern Railway Track*. vol. Second Edition. Delft University of Technology: MRT-Productions.

Hibbit K. & Karlsson (2000). *ABAQUS User's manual Version 6.1.*

Ismail M. (2016). *A New Railway Deck-Track in Sinai at East Port Said on Very Soft Clay*. Journal for New Generation Sciences, (accepted for publication).

Ju S.H., Liao J. R., and Ye Y. L. (2010). *Behavior of ground vibrations induced by trains moving on embankments with rail roughness*, Soil Dynamics and Earthquake Engineering, vol. 30, no. 11, pp. 1237–1249.

Karg C., François S., Haegeman W., and Degrande G. (2010). *Elasto-plastic long-term behavior og granular soils: Modelling and experimental validation*. Soil Dynamics and Earthquake Engineering, 30:635–646.

Lysmer J. & Kuhlemeyer R. (1969). *Finite Dynamic Model for Infinite Media.* J Eng Mech Div, ASCE 95(4):859–78.

Madshus C. & Kaynia A. (2000). *High speed railway lines on soft ground, dynamic behavior at critical speed*. J Sound; 231: 689–701.

Madshus C., Lacasse S., and Harvik L. (2004). *Geodynamic challenges in high speed railways projects*. ASCE Proc Geotechnical Engineering for Transportation Projects (GSP 126).

Peter K., Laghrouche O. and El-Kacimi A. (2013). *The Development and Mitigation of Ground Mach Cones for High Speed Railways.* 11th International Conference on Vibration Problems, Lisbon, Portugal, 9-12.

Shahin A. (2008). *Investigation into Some Design Aspects of Ballasted Railway Track Structure*. Dep. of Civil Engineering, Curtin University of Technology, Perth, WA 6845, Australia.

Takemiya H. (2003). *Simulation of track-ground vibrations due to a high-speed train: the case of X-2000 at Ledsgard*, Journal of Sound and Vibration, vol. 261, no. 3, pp. 503–526.

Woldringh R., and New B. (1999). *Embankment Design for High Speed Trains on Soft Soils*. Geotechnical Engineering for Transportation Infrastructure, Barends et al (eds), Balkema, Rotterdam.