Numerical Modelling for Twin Horizontal Circle Tunnels Under Static and Dynamic Loads

Jaafar Mohammed and Eva Hrubesova

Abstract According to recent studies and observed failures of underground structures, many researchers have addressed the design and construction of tunnel lining against static/dynamic loads and earthquake vibration to get the safety of these structures. Therefore this paper includes the study of the behavior of tunnel lining due to static and dynamic loads. Inner diameter of tunnel is D m. Concrete lining of thickness 0.3 m. The depth of the tunnel centre line from the ground level is 10 D below the surface of the ground, the twin tunnel centre are 3D. After tunnel model is created in the software MIDAS GTS NX, the model is run to analyze the tunnel stability and deformation in static and dynamic conditions by calculating the value of each mesh node based on 3D finite element method and were undertaken to investigate the seismic tunnel response conditions to compare the results in the displacement, stresses, forces and bending moments acting on the tunnel lining. Due to the application of the static load the stress–strain state around the tunnel periphery is changed, the primary stress state is disrupted and the potential of instability increases, otherwise the result shows that the applied dynamic stress is not negligible for underground structure, but it is less dangerous in comparison with the others.

Keywords Static load · Dynamic load · Tunnel · Earthquake · FEA Displacement

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1 Introduction

This case study deals with the static and dynamic analysis of twin circle tunnels that use shield Tunnel Boring Machine (TBM) are predicted, the construction stages and parameters such as gravity, drilling or excavation pressure, jack thrust are applied on the shield excavation, the shield external pressure and segment external pressure are applied around the tunnel which are simulated in a 3D finite elements analysis utilizing MIDAS G1TS NX software and both the face and grout pressures are the most influencing parameters. After tunnel modelling the calculation is run to analyze the tunnel stability by calculating the value of each mesh node based on 3D finite element method, to simulate the effect of earthquake on tunnel stability and displacement. Most of researchers explain that shallow tunnels suffer higher damage compared to deep structures. Many numerical analyses were carried out in order to verify and compare the stresses, forces and bending moments acting on the tunnel lining according with the seismic design. In this subject, twin tunnel were studied by more authors like [1–13].

Response spectrum analysis expresses the natural period, natural angular frequency or natural frequency at the maximum physical quantity response as a function when a dynamic load is applied to the structure. The analysis can be expressed as a displacement response spectrum, pseudo-rapidity response spectrum or pseudo-acceleration response spectrum [14].

Understanding the behavior of tunnel structures during seismic load is one of the most interesting challenges in geotechnical engineering. While tunnels generally performed during earthquakes better than structures on the ground surface, some examples of damage, some of these important structures during previous earthquake events, that is, the 1995 Kobe, Japan earthquake, the 1999 Chi Chi, Taiwan earthquake, the 1999 Bolu, Turkey earthquake, the 2004 Baladeh, Iran earthquake, the 2008 Sichuan, China earthquake, and recently the 2014 Valparaiso, Chile earthquake, highlights the need to account for seismic loading in the design of underground structures [15].

In static analysis, when analyzing a model with infinite material such as ground, boundaries are set far enough from main analysis area. But in dynamic analysis since effect of waves reflection occurs, if boundaries are set in the same way as static analysis, big error may occur [14].

Static and dynamic plane strain finite element (FE) analyses were undertaken to investigate the seismic tunnel response at two sections and to compare the results with the post-earthquake field observations. The predicted maximum total hoop stress during the earthquake exceeds the strength of shotcrete in the examined section. The occurrence of lining failure and the predicted failure mechanism compare very favourably with field observations [16].

In recent years, many tunnels have been built in urban environments; this often involves the construction of twin tunnels in close proximity to each other. In addition, in many cases, the new tunnel is often excavated adjacent to an already existing one. Most of them are twin horizontal tunnels. However, in some cases, the twin tunnels are stacked over each other in order to avoid the pile foundations of existing building on the ground surface [15].

2 Definition of Ground and Structural Materials

This paper studies the 3D model with gravity in Z direction. The thickness of concrete lining is 0.3 m. Distance between the tunnel centre line and ground surface is 10 D. Water table was not considered in the calculation. Tunnel simulation had 47 stage sets. Tables 1, 2 and 3 are presented the mechanical and physical properties of material for ground and structure used in modelling for tunnels. Applied static loads [gravity, drilling or excavation pressure (200 kN/m^2), and the jack thrust (−4500 kN/m^2), are applied on the shield excavation face. The shield external pressure (50 kN/m^2) and segment external pressure (1000 kN/m^2)] are applied around the tunnel as shown in Fig. 15 [14]. The dimension of the model are (x = 210, z = 210, y = 80) m.

Table 1 Ground materials

Name	Soft rock	Segment
Material	Isotropic	Isotropic
Model type	Elastic	Elastic
Elastic modulus (E) [kN/m^2]	20,000	20,000,000
Poisson's ratio (ν)	0.4	0.2
Unit weight (γ) [kN/m^3]	18	24
Drainage parameters	Drainage	Drainage

Table 2 Structure materials

Name	Steel	Grout
Material	Isotropic	Isotropic
Model type	Elastic	Elastic
Elastic modulus (E) [kN/m^2]	25,000,000	15,000,000
Poisson's ratio (ν)	0.25	0.3
Unit weight (γ) [kN/m^3]	78	23

Table 3 Ground properties

Material	Soil	Segment
Type	3D	3D

3 Simulation and Calibration of the Numerical Model

The overview of modelling steps consists of: (1) definition of input parameters and constitutive models for ground, segment, shield and grout, (2) geometry generation using solid elements for ground and tunnel segments, (3) mesh generation using auto meshing, (4) load definition (gravity, drilling or excavation pressure, jack thrust, shield external pressure and segment external pressure), (5) setup construction sequence, (6) define construction stage analysis control, and final run, (7) created eigenvalue and (8) created response spectrum. The construction process can be divided in construction stages with a length of a tunnel ring about 2 m long, in each of these stages the same steps are repeated. The calculation consists of a number of stages, each of which models the same parts of the excavation process. The support pressure at the tunnel face needed to prevent active failure at the face, the installation of the tunnel lining and the grouting of the gap between the soil and the newly installed lining. Construction stage that will be considered as the in situ condition and check the displacement reset condition consideration.

The calculated in situ stress is in equilibrium with the self-weight and the same boundary conditions are used in singular analysis for analysis. The default damping ratio is applied to all modes that have a lower priority than the specified mode. If the input damping ratio is different from the damping ratio of the response spectrum function, the spectrum data is adjusted with reference to the input damping ratio and used for analysis [14].

4 Three-Dimensional FEM Modelling

The FE mesh of the soil and tunnel lining are shown in Figs. 1, 2, 3, 4, 5 and 6. An 80 m long tunnel has been modelled in soft rock with tunnel lining thickness of 300 mm; the depth of tunnel centre line from the ground surface is 140 m.

Gravity 9.81 m/s^2 is applied globally on the model, while the two tub tunnels are subjected to static loads [gravity, drilling or excavation pressure, jack thrust are applied on the shield excavation face, the shield external pressure and segment external pressure are applied around the tunnel]. A 20,000 kN/m^2 of elastic modulus and a Poisson's ratio of 0.4 are used.

Eigenvalue analysis is used to analyze the inherent dynamic properties of the ground/structure including damping parameters, and this can be used to obtain the natural mode (mode shape), natural period (natural frequency), modal participation factor, etc., of the ground/structure. These properties are determined on the basis of the mass and stiffness of the structure. In other words, if a structure is determined, the natural frequency and vibration mode (natural mode) are also determined and the number of properties is the same as the degree of freedom of the structure. For real cases, the structure does not vibrate at a single mode shape and multiple modes overlap to display a complex vibration shape [14].

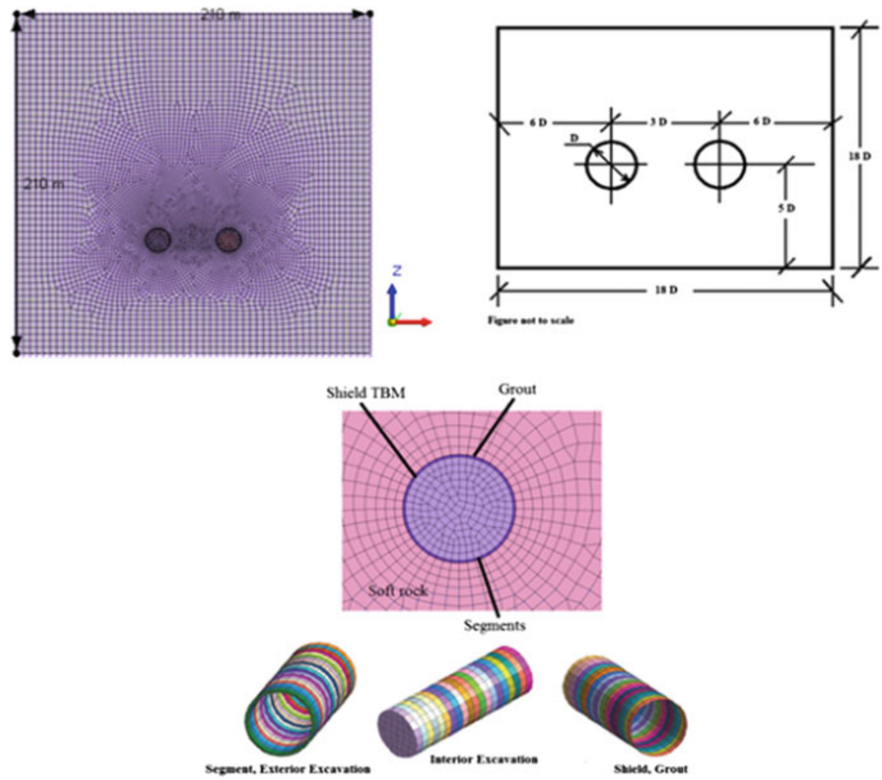

Fig. 1 Mesh tunnel profile

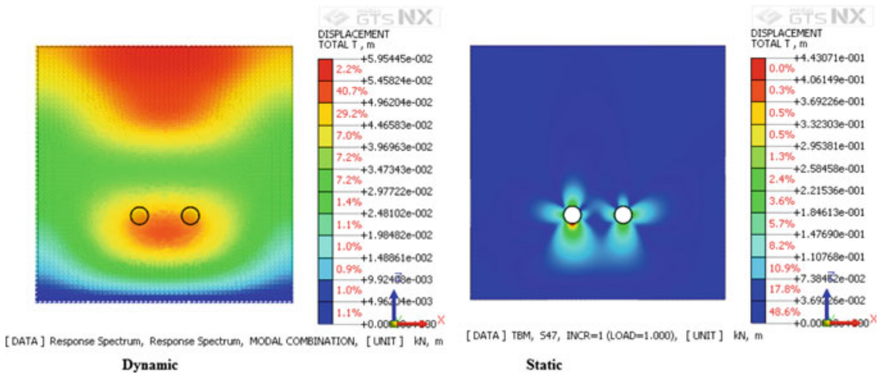

Fig. 2 Total displacement distribution in static and dynamic analysis

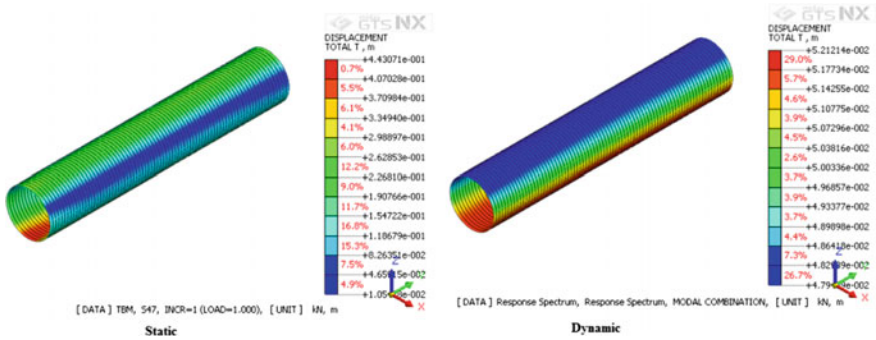

Fig. 3 Total displacement distribution in static and dynamic analysis on the shield of first tunnel

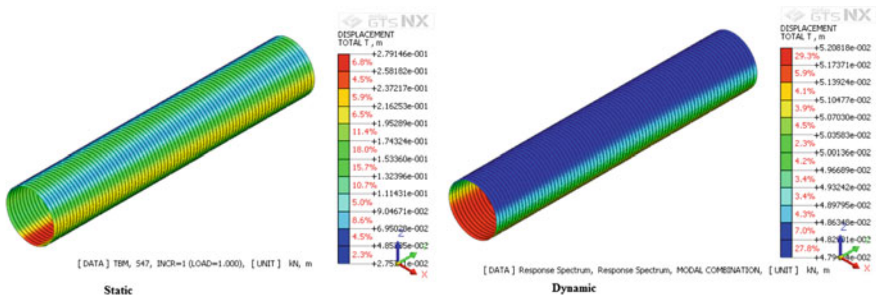

Fig. 4 Total displacement distribution in static and dynamic analysis on the shield of second tunnel

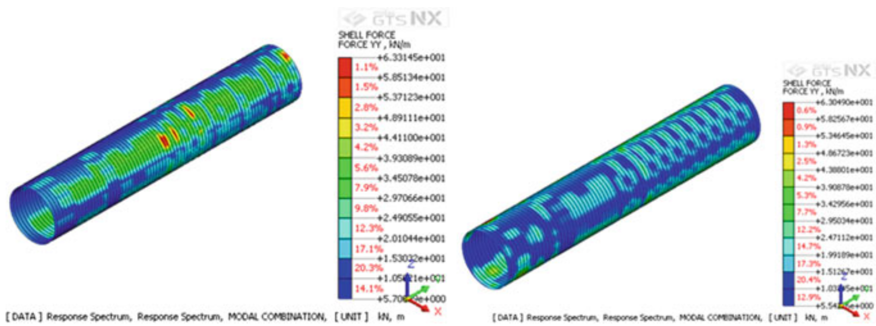

Fig. 5 Force distribution in dynamic analysis on the shield of first and second tunnel

In Figs. 7, 8, 9, 10, 11, 12, 13 and 14, the distribution of (displacement, force, bending moment and shear) in static and dynamic analysis for both tunnels is shown (Fig. 15). Due to the application of the static/dynamic loads on tunnel the distribution on periphery is changed, therefore the balance is disrupted and the

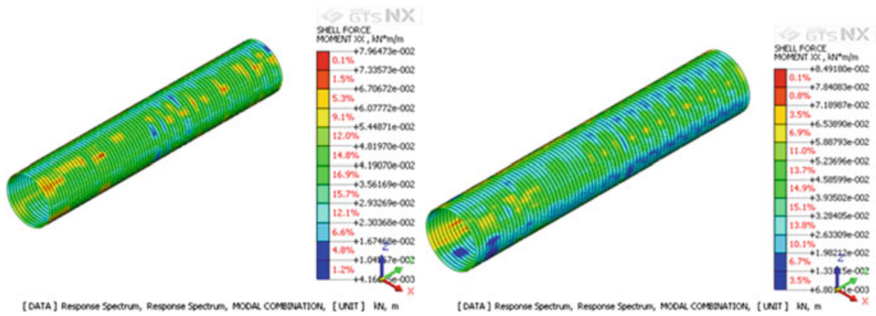

Fig. 6 Bending moment distribution in dynamic analysis on the shield of first and second tunnel

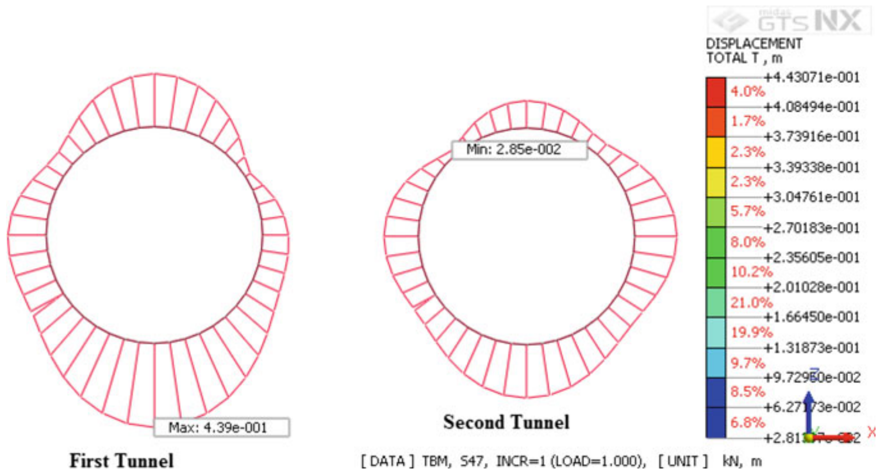

Fig. 7 Displacement distribution in static analysis on the face of shield tunnel

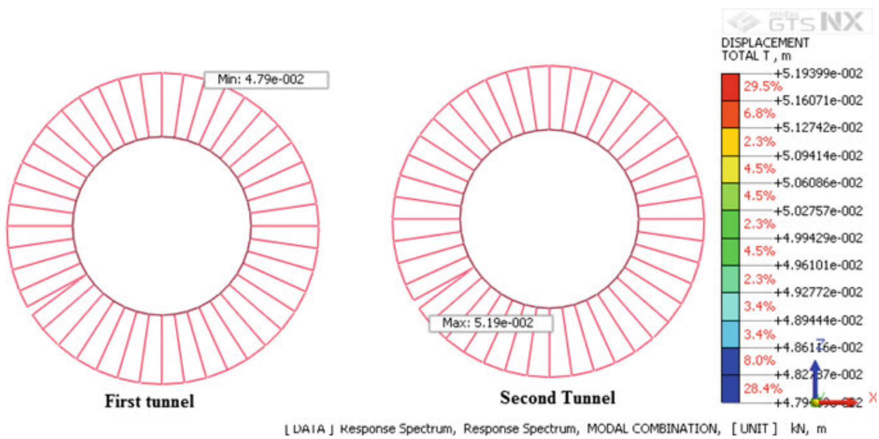

Fig. 8 Displacement distribution in dynamic analysis on the face of shield tunnel

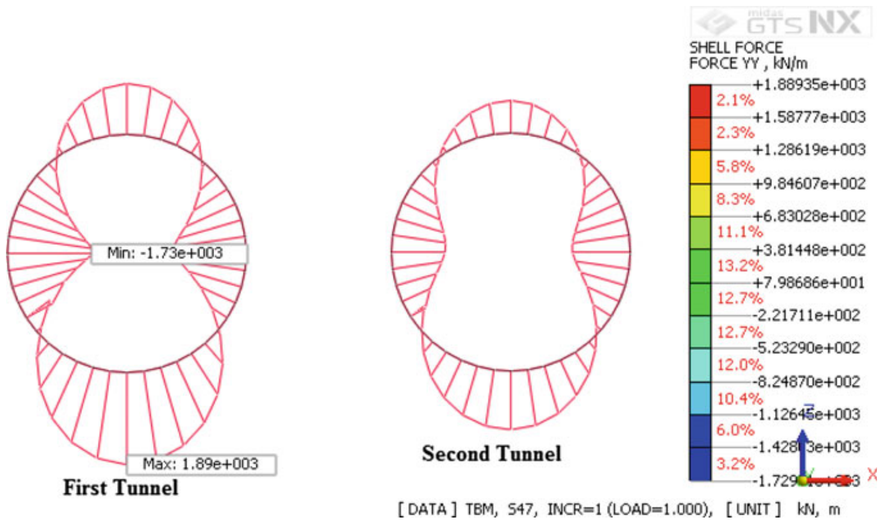

Fig. 9 Force distribution in static analysis on the face of shield tunnel

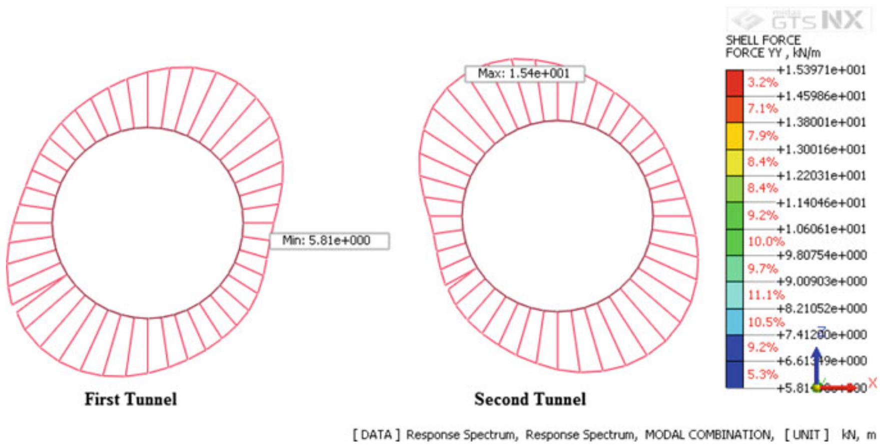

Fig. 10 Force distribution in dynamic analysis on the face of shield tunnel

potential of instability increases, otherwise the result show briefly in Tables 4, 5, 6 and 7. Design Response Spectrum of UBC (1997) is used as seismic response spectrum as shown in Fig. 16.

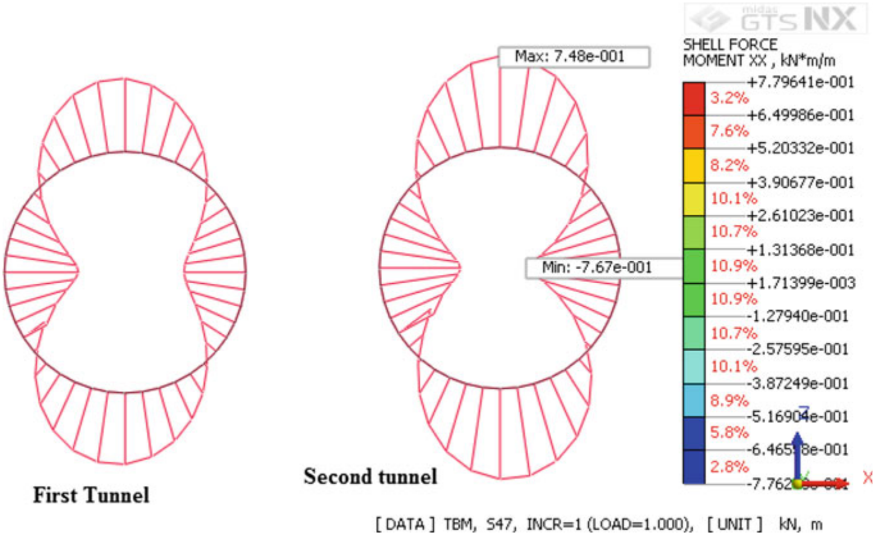

Fig. 11 Bending moment distribution in static analysis on the face of shield tunnel

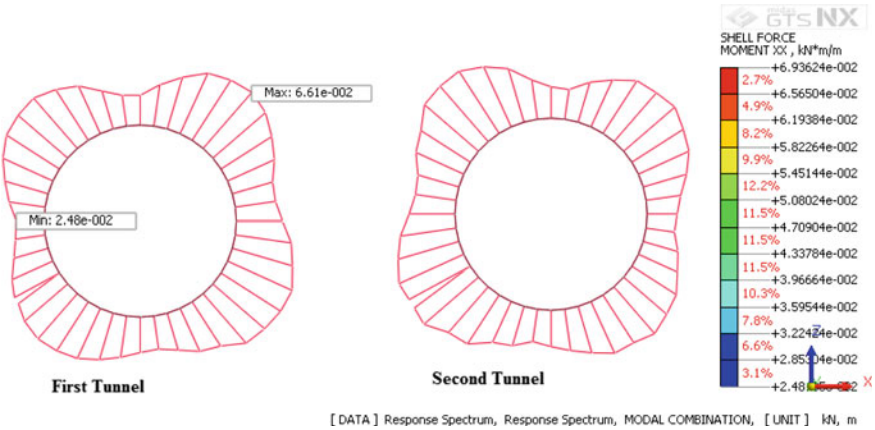

Fig. 12 Bending moment distribution in dynamic analysis on the face of shield tunnel

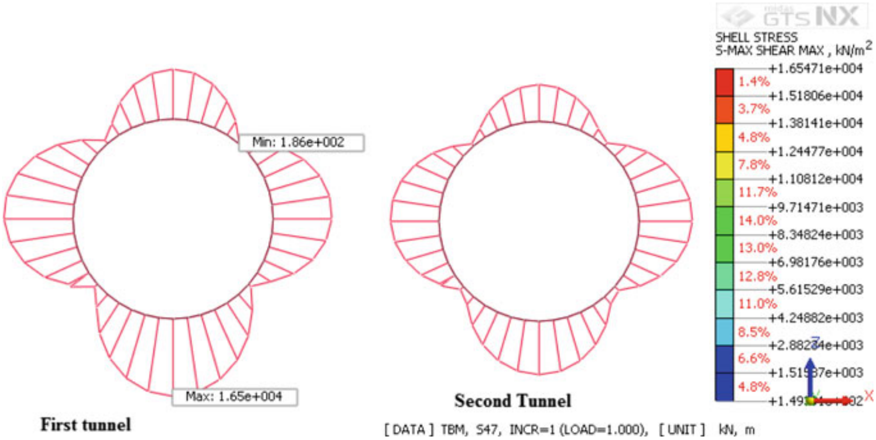

Fig. 13 Shear distribution in static analysis on the face of shield tunnel

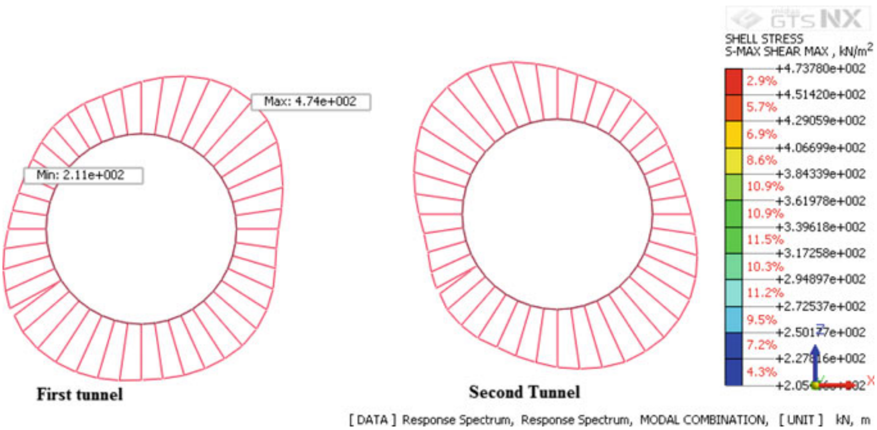

Fig. 14 Shear distribution in dynamic analysis on the face of shield tunnel

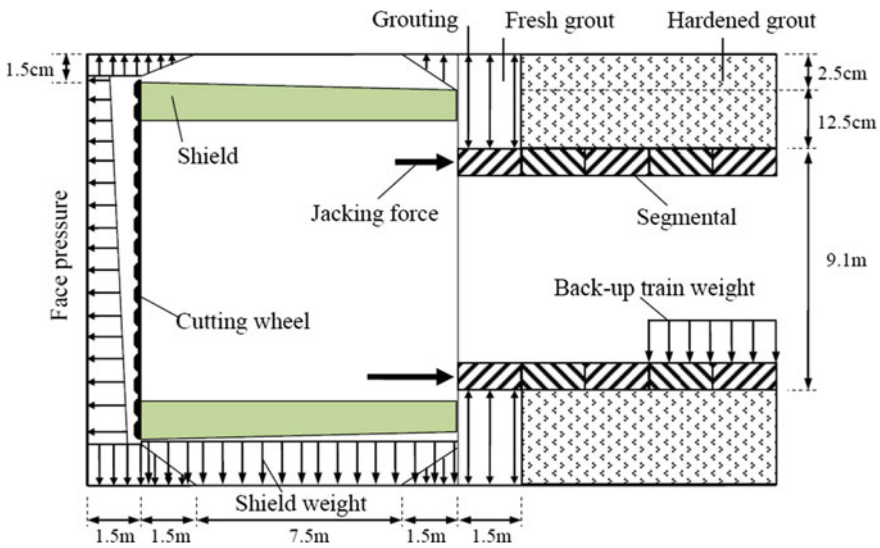

Fig. 15 Layout of the proposed TBM model (not scaled) [15]

5 Conclusions

Based on the tunnel modelling using software MIDAS GTS NX, the 3D analysis of the tunnel response under static and dynamic conditions was performed to investigate the seismic tunnel response to compare the results of the displacement, stresses, forces and bending moments acting on the tunnel.

They provide very good results when tunnelling conditions are known by using numerical analysis. During the shield TBM excavation, it is assumed that the excavation pressure and the jack thrust are applied on the shield excavation face. The shield external pressure and segment external pressure are applied around that face.

The effects of different factors on circular tunnels lining, including elasticity modulus (E), Poisson's ratio (v), unit weight (γ), rock conditions, and tunnel diameters (D), etc., are studied through the numerical analysis solution. In this study, the following conclusions are drawn: Figs. 2, 3 and 4 show the displacement in static and dynamic conditions. Due to the application of the static load, the stress–strain state around the tunnel periphery is changed, the primary stress state is disrupted and the potential of instability increases.

In Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13 and 14, the distribution of (displacement, force, bending moment and shear) in static and dynamic analysis for both tunnels is shown. Due to the application of the static/dynamic loads on tunnel the distribution on periphery is changed, therefore the balance is disrupted and the potential of instability increases, the result is shown briefly in Tables 4, 5, 6 and 7, otherwise

Table 4 The result of distribution in static analysis on both tunnels

Case	First tunnel	Second tunnel
Displacement	Has the Maximum value which is (0.439 m). Bottom is more affected than top. Left side more affected	Has Minimum value which is (0.0285 m). Bottom is more affected than top. Right side more affected
Force	Have maximum (1890 kN/m) and minimum (−1730 kN/m) value. Bottom is more affected than top	Bottom is more affected than top
Bending moment	Approximate the distribution is in uniform	Have maximum (0.748 kN m/m) and minimum (−0.767 kN m/m) value. Approximate the distribution is in uniform
Shear	Have maximum (16500 kN/m^2) and minimum (186 kN/m^2) value. Bottom is more affected than top. Left is more affected	Bottom is more affected than top. Approximate the distribution is in uniform
Unit weight (γ) [kN/m^3]	78	23

Table 5 The result of distribution in dynamic analysis on both tunnels

Case	First tunnel	Second tunnel
Displacement	Has the minimum value (0.0479 m). Approximate the distribution is in uniform	Has maximum value (0.0519 m). Approximate the distribution is in uniform
Force	Have minimum value (5.81 kN/m). Approximate the distribution isn't in uniform	Have maximum value (15.4 kN/m) value. Approximate the distribution isn't in uniform
Bending moment	Have Minimum value (0.0661 kN m/m) and Minimum value (0.0248 kNm/m). Approximate the distribution isn't in uniform	Approximate the distribution isn't in uniform
Shear	Have maximum value (474 kN/m^2) and minimum value (211 kN/m^2). Approximate the distribution isn't in uniform	Approximate the distribution isn't in uniform

Table 6 The maximum value for both shield tunnels

Case	First tunnel (left)			
	Displacement (m)	Force (kN/m)	Bending moment (kNm/m)	Shear (kN/m^2)
Static	0.443071	1889.35	0.600271	16547.1
Dynamic	0.0521214	63.3145	0.0796473	498.198
Case	Second tunnel (right)			
	Displacement (m)	Force (kN/m)	Bending moment (kNm/m)	Shear (kN/m^2)
Static	0.279146	1201.32	0.779046	11435.1
Dynamic	0.0520818	63.049	0.084918	515.513

Table 7 The minimum value for both shield tunnels

Case	First tunnel (left)			
	Displacement (m)	Force (kN/m)	Bending Moment (kNm/m)	Shear (kN/m^2)
Static	0.0105478	−1731.63	−0.607041	2.25958
Dynamic	0.0479459	5.70099	0.00416665	185.678
Case	Second tunnel (right)			
	Displacement (m)	Force (kN/m)	Bending Moment (kNm/m)	Shear (kN/m^2)
Static	0.0275741	−1178.71	−0.77524	2.25897
Dynamic	0.0479454	5.54226	0.00680181	189.299

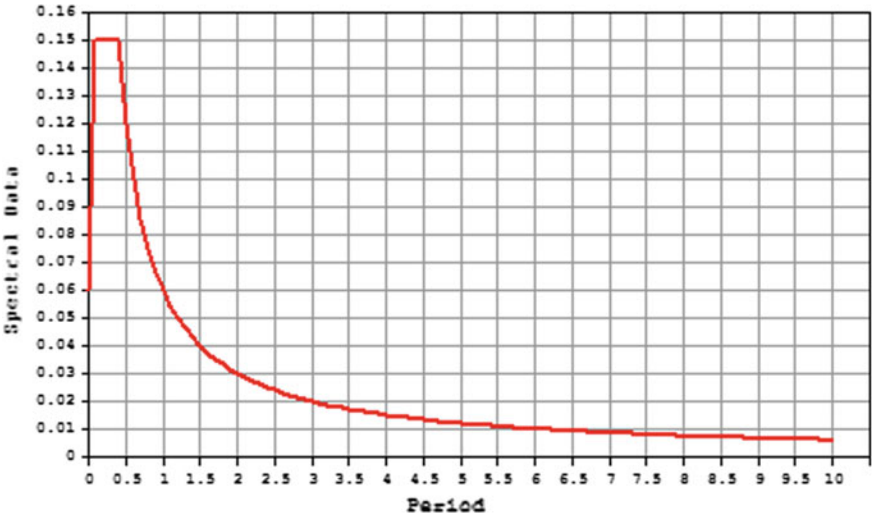

Fig. 16 Modified response spectrum using UBC (1997); damping ration = 0.05; seismic coefficient: Ca = 0.06 Cv = 0.06; normalized acceleration [14]

the result shows that the applied dynamic stress is not negligible for underground structure, but it is less dangerous in comparison with the superstructure.

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