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Application of Hyperstatic Reaction Method for Designing of Tunnel Permanent Lining, Part II: 3D Numerical Modelling

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Abstract

Underground structures often have abrupt changes in structural stiffness or ground conditions such as junctions of tunnels, tunnel portal in slopes, and niches in road tunnels. At these locations, stiffness differences may subject the structure to differential movements and generate stress concentrations. Because of adversity in these issues, they need a three dimensional analysis. This paper proposes a numerical approach to the Hyperstatic Reaction Method (HRM) for three dimensional analysis of permanent tunnel linings Designing is done for Manjil-Rudabar freeway project, Tunnel No. 2. The numerical analyses performed for Operational Design Earthquake (ODE) and Maximum Design Earthquake (MDE) loading conditions. Then, an interaction diagram between axial force and bending moment was used for investigating the capacity of tunnel lining. The numerical results showed that although more axial forces are created in tunnel lining for ODE condition (due to higher load factors in this condition), the points inside the P-M diagrams are located in the furthest distance to the border (tunnel supporting system); because the little bending moment in this condition. Therefore, the safety factor in ODE condition is more than MDE condition. This numerical processing presented that the HRM is a proper, fast, and practical method for tunnel designers.

Keywords: Hyperstatic Method; Tunnel Lining; 3D Numerical Modeling; Static Analysis; Dynamic Analysis.

1. Introduction

The most important goal of a tunnel design is to provide the designer with an understanding of the mechanism of behaviour during tunnelling, including the possibility of risks and where they could occur, and a basis for producing a robust and safe design and, finally, a basis for interpreting the monitoring results [1]. Because of the uncertainties concerning the properties of the ground and the induced loads on the lining, it is important to highlight that there is not a single analysis method that can be used for all tunnels, and very often the precision of the available analytical and numerical tools is much greater than the reliability and the accuracy of the data obtained from site investigations and rock mass characterization.

Therefore, designers are obliged to undertake sensitivity analysis of the ground–support interaction model in order to understand the influence of the input parameters.

The most frequently used lining design methods in tunnelling practice are AFTES (1976), USACE (1997), and BTS (2004) [1-3].

Underground structures often have abrupt changes in structural stiffness or ground conditions. Some examples include: (a). connections between tunnels and buildings or transit stations; (b). junctions of tunnels; (c). traversals between distinct geologic media of varying stiffness; (d). tunnel portal in slopes; and e) niches in road tunnels. At these locations, stiffness differences may subject the structure to differential movements and generate stress concentrations. The design will also have to account for potential of pounding between the structure and the connecting tunnel due to differential movement. Because of adversity in these issues, they need a three dimensional analysis. In this paper, special topics of 3D of tunnels are presented by using hyperstatic reaction concepts for simulating of complex sections of tunnel linings. This method has frequently been used, despite the structural

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engineer's perplexity as to the distinction between the zone exposed to ground actions and the zones exposed to ground reactions to support displacements.

The hyperstatic reaction method (HRM) also known as the bedded-beam-spring model presents some disadvantages, such as the difficult to correct evaluate the spring stiffness (that is the object of the present investigation) and the loads to be applied to the lining, which has to be evaluated independently from the deformation of the system using, e.g., dead load approaches or rock mass classifications. Despite these drawbacks, this approach is widely applied in design practice thanks to its ease of use, and the possibility of obtaining a quick and simple evaluation of the actions inside the structural elements by varying the acting loads, and thus carrying out sensitivity analyses, that is, as mentioned before, of primary importance [4].

The HRM is developed by different researches. Do et al. [5] improved the HRM proposed by Oreste [6] to investigate the behaviour of segmental tunnel lining, in which the effect of segmental joints was considered indirectly through the use of a reduction factor applied to the flexural rigidity of the lining. These researchers also developed a specific implementation using a FEM framework for segmental tunnel lining. The numerical results showed that the proposed HRM can be used to effectively estimate the behaviour of a segmental tunnel lining [7].

In this paper, the applications of HRM are presented for designing of tunnel lining in complex sections such as tunnel portal, intersections, and niches. A real case study (Manjil-Rudabar freeway project, Tunnel No. 2) is designed by this method.

2. The Case Study (Rudbar-Manjil Freeway, Tunnel No. 2)

The Manjil-Rudabar freeway is one of the civil projects under construction in Iran. To complement the Rudbar – Manjil freeway, the construction of two twin tunnels has been predicted. In this paper, the tunnel permanent lining is designed for Tunnel No. 2. The length of the tunnels is more than one kilometer. The width of the right and left tunnels are 14 and 12 m, respectively.

Based on geological longitudinal profile of Tunnel No. 2, there are some lithology units at the tunnel elevation including pyroclastic andesitic rocks with tuff and tuff-breccia faces. In this paper, 3D analyses related to Tunnel No.2 are performed. These sections are the weakest rocks with different overburdens. The rock mechanics properties of sections for numerical analysis are illustrated in Table 1. The earthquake acceleration for the maximum and operational design earthquakes (ODE and MDE) conditions is considered 0.22 g and 0.35 g, respectively.

Table 1. Rock mechanics properties of tunnel sections

Parameter	Unit	Portal & Niche	Intersection
Elastic Modulus	GPa	1.2	0.5
Density	kN/m^3	25	26
Cohesion	kPa	450	180
Friction Angle	Degree	35	30
Passion’s ratio	-	028	0.3
Overburden	m	40	60

3. Tunnel Lining Designing and 3D Numerical Simulation

Structural analysis is a major part of tunnel lining designing. The Japan Society of Civil Engineering (JSCE) is presented the following points for structural analysis [8]:

(i) Structural analysis for seismic design should be conducted using appropriate structural models.

(ii) The ground motion should be appropriately quantified so as to conform to the method used to analyze ground vibration and also consider interactions between the tunnel and the surrounding ground.

(iii) Member forces from a structural analysis for seismic design should be superimposed on ordinary member forces to obtain a design member force. If nonlinearity of structural members is considered in seismic design, the structural analysis is performed setting ordinary design member forces as the initial member forces. In this case, the ordinary design member forces are those of the serviceability limit state.

3.1. Spring Stiffness in HRM

The Winkler foundation model has been the simplest and most widely used spring model and is often referred to as the “one-parameter” foundation model. In the Winkler foundation model, reactive forces of the foundation are assumed to be proportional at every point to the deflection of the beam at that point. Besides the soil-structure interaction problems, the beam-Winkler foundation model can be used to simulate behaviours of several engineering problems [9].

The HRM assumes the hypothetical existence of normal and shear springs all around the support (Winkler’s approach) (Figure 1). These develop forces that linearly depend on the relative displacements between the structure and the rock mass; having reached a limit stress condition, which is a function of the rock mass strength, any increment in the relative displacements do not produce any further increment in the forces (plastic stage in the rock mass–structure interaction). The normal springs disappear in zones where the support structure moves towards the tunnel: this is generally the case of the roof, but when the horizontal active loads are greater than the vertical ones, it occurs at the sidewalls. Therefore, only compressive loads are possible in the normal direction, where the tunnel support moves towards the rock mass: normal springs only work in compression [10].

The stiffness of the springs K_n and K_t (Figure 1) are usually evaluated from the rock mass data (Table 1) using very simple relationships as those derived from Winkler theory [3,11]. For example, USACE (1997) suggests using [3]:

$$K_n = \frac{E}{R_{eq}(1+v)} \tag{1}$$

$$K_t = \frac{1}{3} K_n \tag{2}$$

While Oreste suggests [7]:

$$K_n = \frac{E}{2R_{eq}}(\frac{1.33}{2}) \tag{3}$$

Where R_{eq} is the equivalent radius of the tunnel, E and ν the elastic modulus and the Poisson ratio of the ground, respectively.

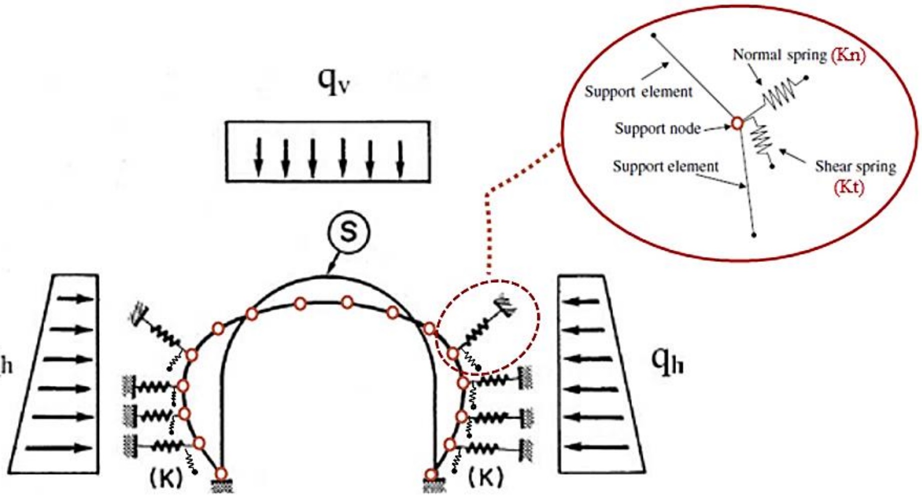

Figure 1. Scheme of the hyperstatic reaction method (Winkler's springs)

Loads Calculation Loads acting on the lining are fairly complex and difficult to evaluate accurately. The general approach usually used for the calculation of earth pressures. Among the earth pressures acting on the tunnel, the design earth pressures determined independently of the deformation of the tunnel. The earth pressure acting on the tunnel bottom is regarded as soil reaction, even if it is determined independently of the deformation of the tunnel [8].

a) Rock Load

The HRM has two drawbacks: the exact evaluation of the active loads q_v and q_h and the definition of the stiffness of the normal and shear Winkler's springs are necessary.

Basically, the vertical earth pressure is uniform load acting on the tunnel crown. When determining the vertical earth pressure acting on the tunnel in the long term, it is preferable not to expect the arch action of the soil/rock when the overburden depth is less than the tunnel diameter. In this case, adoption of the loosening earth pressure for the design earth pressure may be problematic in any kind of soil/rock. Where the overburden is larger than the tunnel diameter, it is possible to adopt the loosening earth pressure for the design vertical earth pressure since the arch action of the soil can be expected.

In general, the equation proposed by Terzaghi is used for the calculation of loosening earth pressure [8].

The active vertical load can be estimated using the convergence- confinement method, by intersecting the ground reaction curve of the tunnel and the reaction line of the support structure. The other methods for calculating of vertical and horizontal loads are empirical methods like rock mass classification such as Q and RMR with considering simple assumptions [12]. These loads are illustrated in Table 2 for different sections.

Table 2. The vertical and horizontal pressure (rock load)

Unit	Vertical Load (ton)	Horizontal Load (ton)
Portal	26	13
Intersection	14	7
Niche	15	8

b) Earthquake load

Since tunnels are exposed to the effects of earthquakes, particular consideration must be given to the tunnel location, condition of surrounding ground, magnitude of seismic motions, tunnel structure and shape and dimension, and any other conditions considered necessary in accordance with the importance of the tunnel and its purpose and use [8].

Generally, the weight of a tunnel is regarded as less than that of a corresponding volume of surrounding ground because the tunnel is hollow. Thus, when a seismic force acts on the tunnel, the force of inertia on the tunnel is assumed to be less than that on the surrounding ground. As a consequence, the behavior of a tunnel under earthquake conditions is regarded as subordinate to the surrounding ground, provided that the tunnel lies below a certain depth at which it can be constrained by the surrounding ground. Therefore, the effects of earthquakes are comparatively small for tunnels with sufficient overburden and in good uniform ground.

A simple method is used for considering earthquake load. Figure 2 shows the loading condition for earthquake loading. Δd_{lining} is induced displacement by earthquake load. It can be calculated by analytical methods that are presented in reference [13]. By considering properties in Table 1, Δd_{lining} for ODE and MDE conditions are illustrated in Table 3.

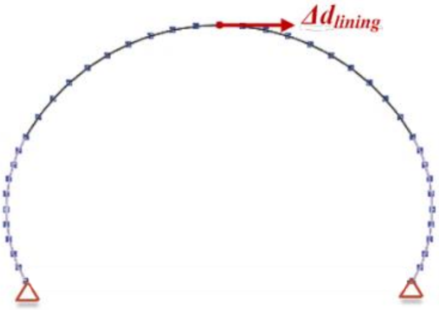

Figure 2. Loading condition for earthquake loading

Table 2. Induced displacement by earthquake load

Section	ODE (mm)	MDE (mm)
Portal	9.3	17.4
Intersection	4.8	9.0
Niche	8.0	14.9

c) Dead Load

Dead weight is a load in the vertical direction distributed along the centroid of the lining. The concrete load is considered 2.5 m^3 for every one cubic meter of concrete.

3.2. Load Combinations

Design loading criteria for underground structures has to incorporate the additional loading imposed by ground shaking and deformation. Once the ground motion parameters for MDE and ODE have been determined, load criteria are developed for the underground structure using the load factor design method. This section presents the seismic design loading criteria for MDE and ODE. The MDE and ODE conditions are [14]:

$U=D+EX+EQ$ *for MDE condition (1)*

$U=1.05D+1.3EX+1.3EQ$ *for ODE condition (2)*

Where *U*, *D*, *EX* and *EQ* are required structural strength capacity, effects due to dead loads, effects due to excavation loads, and effects due to design earthquake motion, respectively.

4. Numerical Results

The numerical model should be verified in the first step. The verification of this method is approved in the "Applications of Hyperstatic Reaction Method for Designing of Tunnel Permanent Lining, Part I: 2D Numerical Modeling" using an analytical method suggested by JSCE. The results showed that there is a good agreement between numerical and analytical methods. So this method can be used for 3D modeling.

4.1. State of Axial Force and Bending Moment

The 3D numerical simulations of tunnels sections: tunnel portal, intersection, and niche. The numerical modelling was performed based on section 3.3 under static and dynamic conditions (ODE & MDE) for three sections by considering hyperstatic reaction concepts. Then, forces are accumulated in nodes based on superposition principle. Figures 3 to 8 show the state of axial force and bending moment under ODE loading in tunnels lining for three sections.

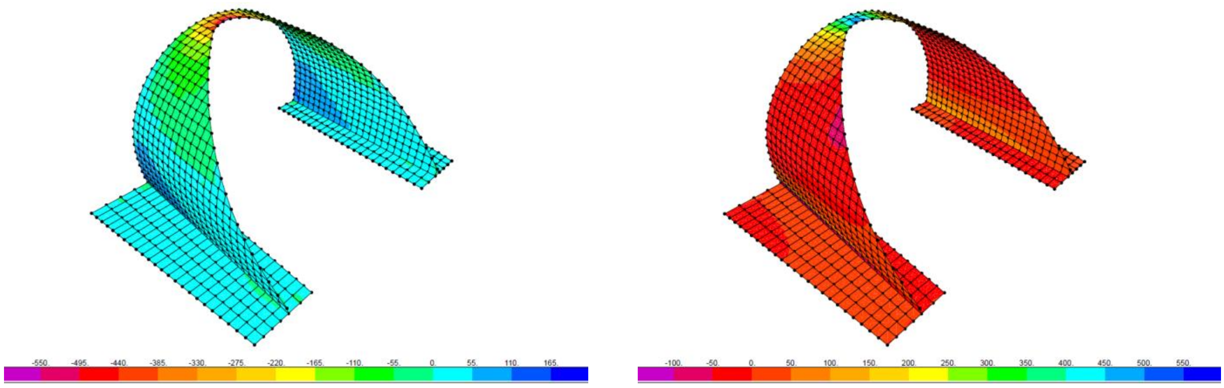

Figure 3. The state of a) axial force and b) bending moment in portal lining in static condition

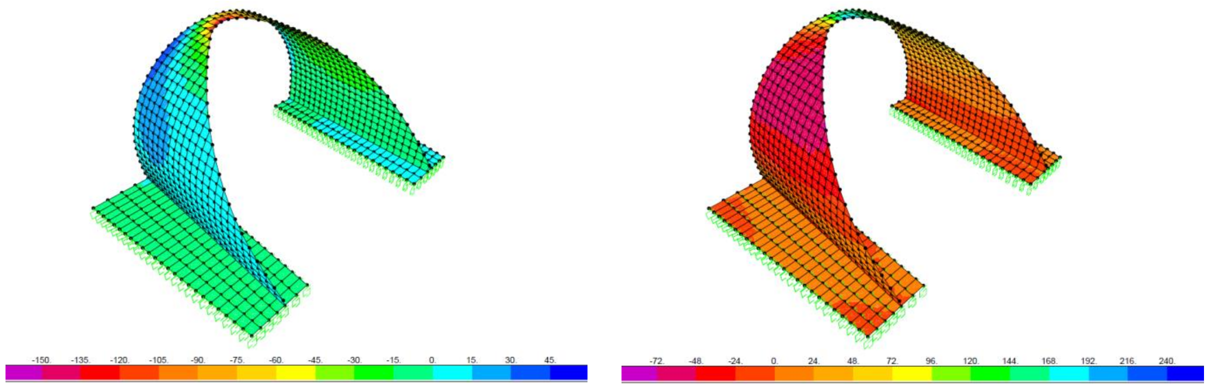

Figure 4. The state of a) axial force and b) bending moment in portal lining in ODE condition

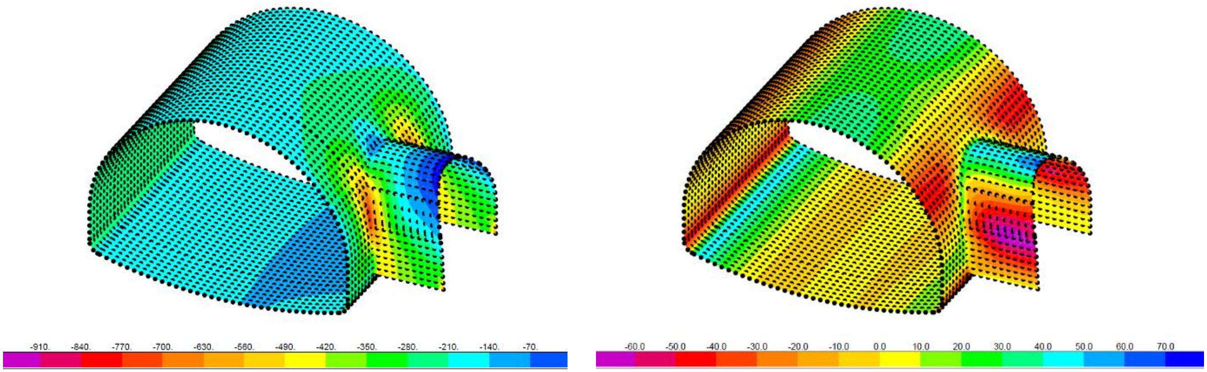

Figure 5. The state of a) axial force and b) bending moment in junction lining under static loading

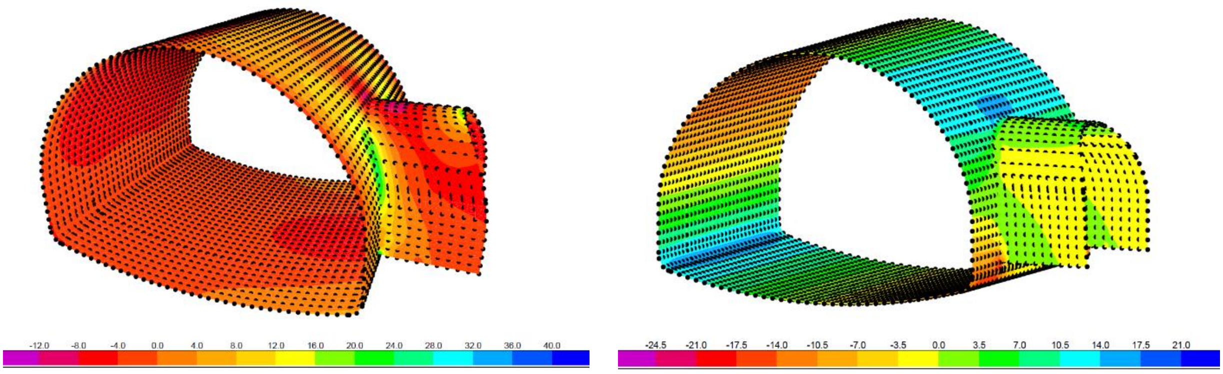

Figure 6. The state of a) axial force and b) bending moment in junction lining under dynamic loading

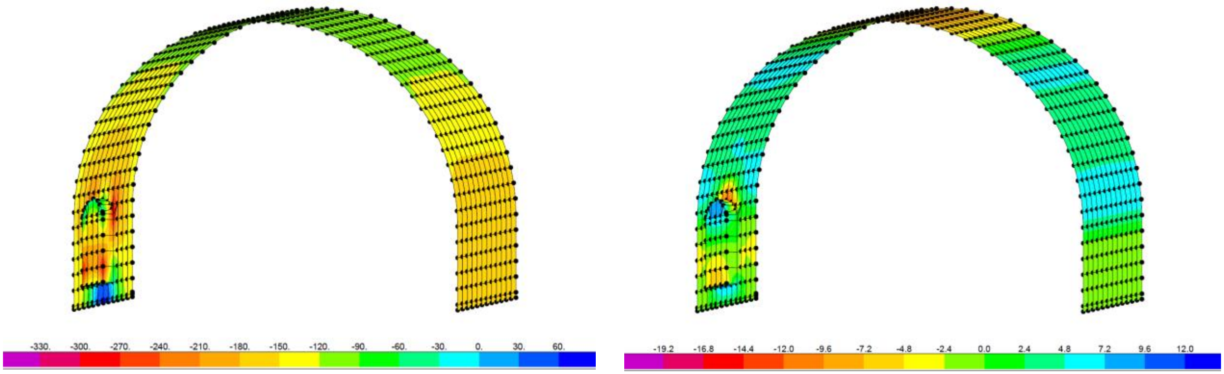

Figure 7. The state of a) axial force and b) bending moment in niche lining under static loading

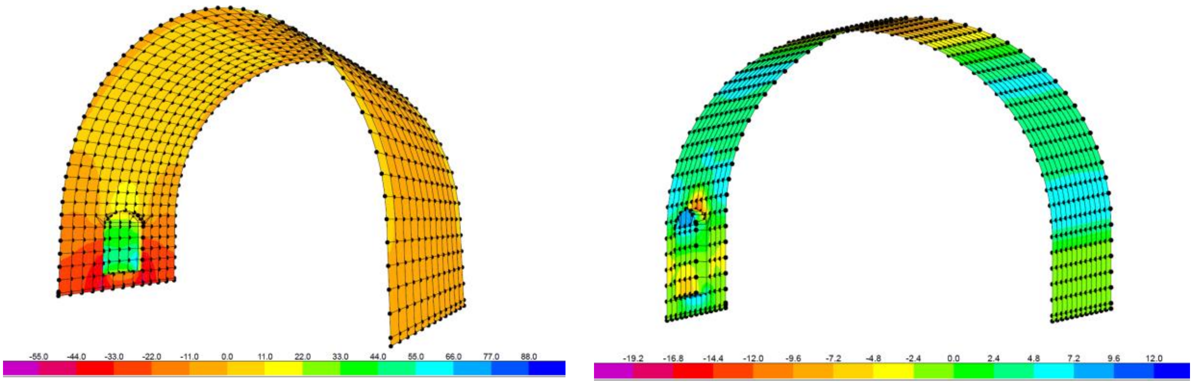

Figure 8. The state of a) axial force and b) bending moment in niche lining under dynamic loading

According to Figure 3-8, maximum of axial force and bending moment occurs in the crown for tunnel portal (i.e. in maximum thickness of lining), in the intersection of main and connection for tunnels junction, and in the corners for niche section because of stress concentration.

The maximum axial force and bending moment for ODE and MDE conditions are illustrated in Table 4.

Table 3. Maximum axial force and bending moment for all sections

Section	ODE		MDE	
	N	M	N	M
Portal	224.5	229.1	155.1	261.8
Intersection	899.7	69.3	518.4	82.8
Niche	330	19.3	264	25.8

*N= Axial force in ton, M= Bending moment in $ton.m$

4.2. Interaction Diagram between Axial Force-Bending Moments

The bearing capacity of the column cross section can be determined from the interaction diagram moment-axial force (M–P). The P-M interaction diagram is a suitable tool for designing and calculating the ultimate capacity of tunnel lining sections in load combination conditions of axial force with bending moment. Figures 9-11 show P-M diagrams for different sections. Due to changing in lining thickness for tunnel portal section (increasing thickness from floor to crown of tunnel), interaction diagrams are calculated for different sections.

According to Figures 9 to 11, tunnels lining is stable under ODE and MDE conditions. These Figures show that although more axial forces are created in ODE condition (due to higher load factors in this condition), the points inside the P-M diagrams are located in the furthest distance to the border (tunnel supporting system); because the little bending moment in this condition. Therefore, the safety factor in the ODE condition is more than the MDE condition.

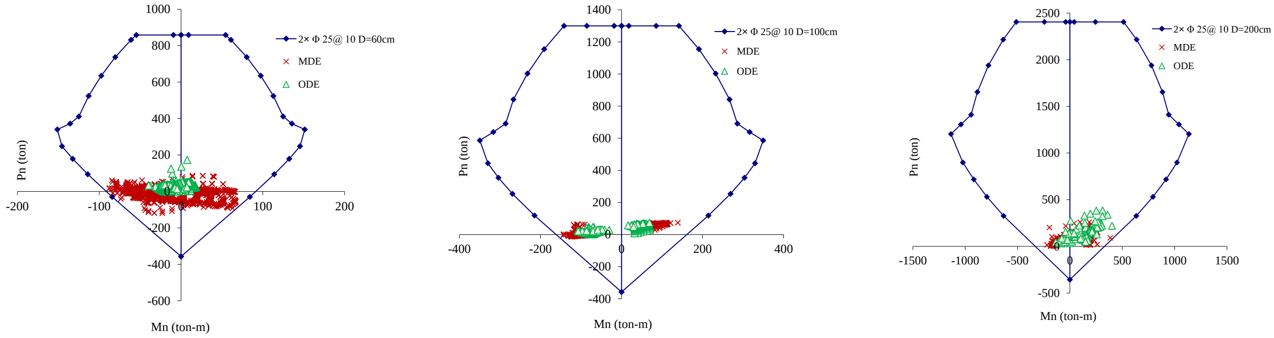

Figure 9. P-M diagrams for tunnel portal (thickness 60, 100 and 200 cm)

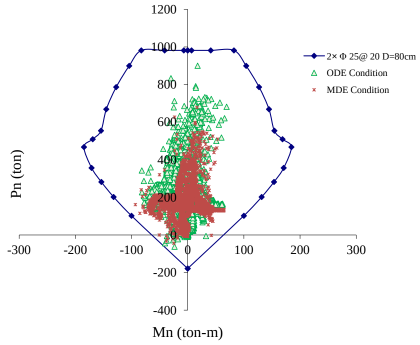

Figure 10. P-M diagrams for tunnel intersection

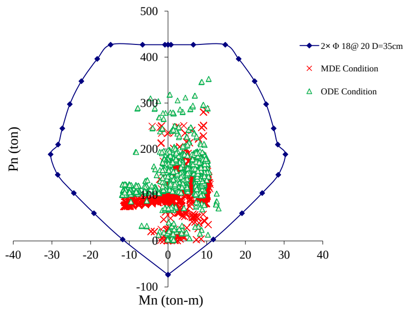

Figure 11. P-M diagrams for niche

5. Conclusion

In this paper, the application of HRM is presented for designing permanent tunnel lining that in which three dimensional analyses can be considered. To introduce the Winkler-based beam element into a three-dimensional tunnel model, an element formulation and a process for determining ground state were performed.

Designing performed for Manjil-Rudabar freeway project, Tunnel No. 2 in three sections including tunnel portal, intersections, and niche. The numerical analyses were performed for ODE and MDE loading conditions. Then, an interaction diagram between axial force and bending moment was used for surveying the capacity of tunnel lining. The proper lining was designed for three sections based on induced forces in tunnel lining. The results showed that although more axial forces are created in tunnel lining for ODE condition, the points inside the P-M diagrams are located in the furthest distance to the border (tunnel supporting system); because the little bending moment in this condition. Therefore, the safety factor in ODE condition is more than MDE condition. The present study has shown that the Winkler-based beam element can be used in a tunnel analysis model. This numerical processing also presented that HRM is a proper, fast, and practical method for tunnel engineers.

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