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Behavior and design of earthquake resistant concrete structure

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Abstract. Earthquake and seismic-resistant concrete structures are essential components and requirements of structural design. The performance and response of concrete structures during/after the earthquake event are significant to determine the condition of the structures as well as to identify the possibility of structural failure. The main objective is to investigate the appropriate method to evaluate the impact on the structure due to earthquakes based on closed-form solutions, and to determine its differences with the results of numerical modelling. The seismic behavior of structures is required to be designed in accordance with the minimum design requirements specified in the Standard. Seismic design, where ground behavior is considered, is presented as a significant part of design analyses, and ground movement and shaking, are associated with the ground deformation which is the primary seismic load consideration for the design of plain or reinforced concrete structures. The outcome of the longitudinal analysis provided the maximum axial and bending strain which is adopted to calculate the combined strain. These results of strain are considered with the design of concrete structures against Ultimate Limit State and Service Limit State design phases. Therefore, the results evaluate the effect of seismic design on the performance of the concrete structure.

Keywords: seismic design, closed form solutions, longitudinal analysis and racking analysis, structural performance and behavior, concrete structure

1. Introduction

Earthquake-resistant concrete structures are an important criterion and requirement for structural design. The performance and response of concrete structures during and after the earthquake event are significant to determine the condition of the structures, and to identify the possibility of structural failure during and after adverse scenario and events, particularly earthquake. The underground structures, including tunnels are typically perform well in earthquakes to resist seismic loading during ground movement, and exclusively damaged by seismic behavior with significant and extensive level. The surface multi-story building, underground moment frame structure, cut and cover structure and shaft structure are designed as the earthquake resistant concrete structure to minimize the extreme damage or collapse caused by earthquake event. The main objective is to investigate and determine the appropriate method to evaluate the impact on the structure due to earthquake based on closed form solutions, practically for varies types of underground structures. Moreover, the purpose is to determine the potential aspect of comparison between closed form solutions and results of numerical modelling. The typical primary ground deformations and movements caused by seismic wave propagation are in

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accordance with three major strain conditions. These components are adopted to evaluate and determine the seismic response and behavior of reinforced concrete structures. Seismic design, where ground behavior is considered, is presented as a significant part of design analyses, and ground movement and shaking, are associated with the ground deformation which is the primary seismic load consideration in the design. The failure of a structure, whether underground or above-ground, could result in a variety of effects, with the worst-case scenario causing tremors and a number of deaths, particularly for large infrastructure. The seismic behavior of underground structures and frame structure buildings are required to be designed in accordance with the minimum design and reinforcement detailing requirement specified in the Standards.

2. Analysis

For various types and classifications of concrete structures, regardless of whether they are above or underground, the relative stiffness of the support systems, including the foundations, base slabs, and tunnel supports, as well as the surrounding ground of soils or rocks, play an important role in determining the underground opening of an earthquake or earth movement that occurs during the earthquake [1].The typical primary ground deformations and movements caused by seismic wave propagation are in accordance with three major strain conditions which are adopted to evaluate to determine the seismic response and behavior of concrete structures, including the longitudinal axial tension and compression forces, the longitudinal bending moment, and ovaling or racking of the structures and structural components[2] .

As a result, the fundamental design approaches for moment frame structures are to investigate the seismic behaviors and responses of columns, bases, and foundations in accordance with ordinary moment resisting concrete frames and intermediate moment resisting concrete frames. Following these two concepts, varies stories and levels of building shall be designed with the minimum design and reinforcement detailing requirement in order to eliminate the cracking and forces caused by earthquake and seismic loading[3].

Moreover, for the underground reinforced concrete structures, two essential approaches are widely adopted with the design to assess and investigate the response of a structure under the implementation of earthquake due to the longitudinal and ovaling seismic deformations, to determine the magnitude of the induced stresses and strains of seismic response. The closed form solution is the approach to be adopted and considered constantly to evaluate the appropriate approximations so as to assess seismically induced strains of the underground concrete structures as shown on Figure 1.Furthermore, as shown in Figure 2 [2,] cutting-edge numerical methods using two-dimensional and three-dimensional software models with soil structure interaction are performing the racking analysis to determine the response of underground concrete structures.

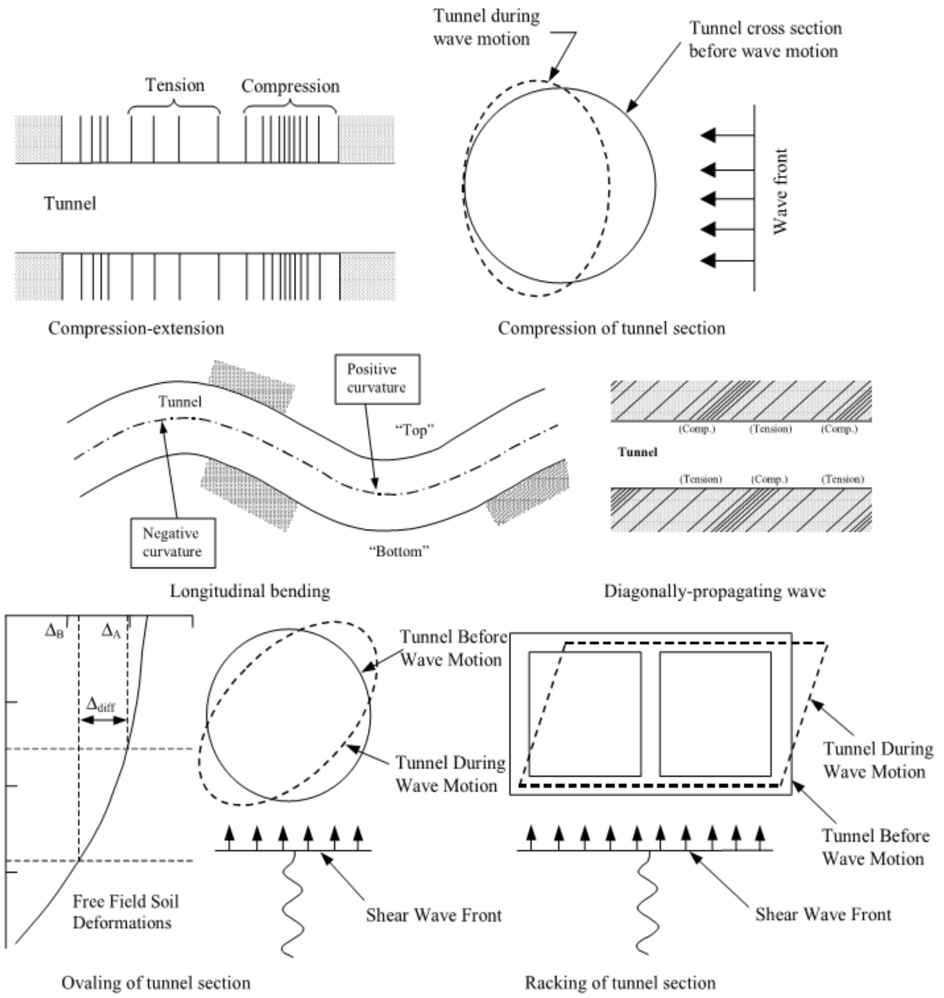

Figure 1. Deformation modes of tunnels due to seismic shaking.

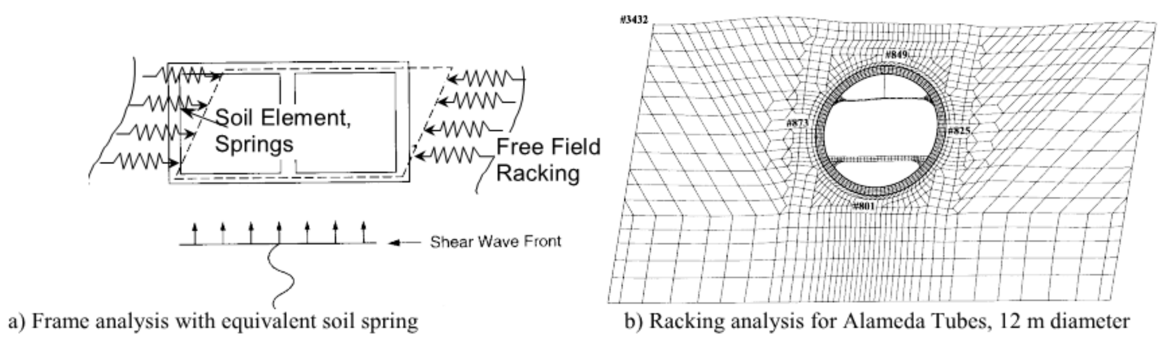

Figure 2. Pseudo static analysis approach.

In accordence with Hashash et al 2001, the ground, including varies of soil or rock classes, free-field shear strain is estimated using the following equation:

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$$\gamma_{\max} = \frac{PGV}{V} \quad (1)$$

Where

$\gamma_{\max}$ = the maximum free-field shear strain

PGV = the peak ground velocity

V = the shear wave velocity for rock unit at the interface of concrete s trcutures and rock or soil

With regards to the longitudinal analysis of seismic design, it is proposed to adopt the simplified closed-form solutions illustrated in the Hashash et al 2001 to determine and estimate the longitudinal strains of concrete structures. The simplified approach assumes the seismic wave field to align with the plane of earthquake waves with the same amplitudes at every location along the interface of concrete structures and ground, however, differing with the arrival time of the seismic wave. Furthermore, in relation to the racking analysis, the racking analysis is performed by adopting the closed-form solutions in order to evaluate and estimate the thrust force or axial force and bending moment of the concrete structures. The closed form solutions with regards to the seismic motions and effects are in accordance with the approach in Hashash et al 2001 [2].

The limitation of the closed form solutions in longitudinal analysis and racking analysis illustrates the exclusion of in-situ stress of the ground. The in-situ stress determination of the ground at the interface between concrete structure and ground materials is not evaluated by the closed form solutions, hence, the structural force from estimation is neglected in the design. Another limitation of the closed form solutions is that the formula is fundamentally based on the regular or circular geometry of the concrete structures connecting the ground. Therefore, the outcome for irregular profiles and shapes of the concrete structures are estimated with general approximates. For the low seismic activities, the approach is considered to be adequate for the fundamental seismic design of the concrete structures [2] .

Also, for the underground concrete structures, the Austroads Guide to Road Tunnels (AGRT) define the four primary earthquake events for tunnels and associated underground structures. The performance and design of underground concrete structures shall comply with the four levels earthquake criteria, including the Operating Design Earthquake (ODE), Maximum Design Earthquake (MDE), the Maximum Credible Earthquake (MCE), and the Operating Basis Earthquake (OBE) [1] .

The MDE illustrates the underground structure is used for emergency traffic under the design return period event. However, it is acceptable that the damage of concrete structures could have occurred, and repair is required immediately while earthquake event is resolved. Therefore, the permanent repair work is to reinstate the structural capacity under design intent for feasibly static and seismic performance of concrete structure[5].

The ODE indicates that the damage caused by an earthquake is minor and avoidable, and the seismic response is within the design intent and structural capacity, implying that the structure's behavior is simply elastic, and thus the concrete structure must remain serviceable after the earthquake event [5].

The OBE is similar to the ODE, where the OBE is representing that the occurrence of earthquake event is potentially during the service life of the underground concrete structure. Thus, the response and behavior of the structure shall be under elastic which results in minimal damage to the concrete and structural elements. The performance of the concrete structure after earthquake shall still comply with the design intent and capacity, so there is no major repair required [5].

The MCE demonstrates the scenario which the tunnel shall not collapse, but it is potentially the occurrence of extensive damage of tunnel after the design return period event less than the earthquake event with return period significantly. The temporary repair is required to allow capable of permanent repair, and the use of emergency traffic is compulsory. Also, the structural capacity of the concrete structure against seismic event is reduced which does not meet the design intent and specification, however, it shall depend on the frequency of the earthquake event at the particular location to determine if the structure is still allowed to operate, as the likelihood of occurrence of earthquake event at certain zone is minor.

3. Discussion

The Australian Standards adopted for the seismic design of concrete structure are AS1170.4, “Structural Design Actions, Part 4: Earthquake Actions in Australia”. In accordance with AS1170.4, above and underground structures are required to be designed to withstand seismic loadings at Ultimate Limit State (ULS) without extensive and significant fault and collapse. The As1170.4 is primarily developed for frame structure building and surface concrete structures which are fundamentally subject to the harmonic earthquake wave motion of induced inertia effects during a seismic event. The serviceability of structure is required to be deemed to comply under the provision of AS1170.4, which the earthquake loads are defined and evaluated in AS1170.4 [6]. Seismic design and analysis are therefore undertaken for ULS for the Maximum Design Earthquake. For the Australian Standards with respects to seismic design of infrastructure, the AS5100.2 is adopted [7]. Moreover, there are other national design standards are relevant to the seismic design to be adopted, including “BS EN 1998, Eurocode 8: Design of structures for earthquake actions”.

While considering a stiff structure, irrelevant to the fact of above or underground structures, the structural elements resist the ground deformations and deform less than the free-field ground deformation. The stiffness of the concrete structure is comparable to the rock and ground stiffness; the deformation and behavior of the structures are comparable to the free-field deformation. Nevertheless, for the flexible concrete structures, particularly surface buildings with high flexibility, this type of structural element deforms more than the free-field ground movement and deformation as the transient of ground deformation is larger than the free-filed deformation.

The seismic response of frame structure and surface building due to the earthquake and ground movement is different from the seismic behavior of underground structure, particularly tunnel. The surface buildings and frame structures are subject to the inertial forces caused by the earth movement during an earthquake, while the underground structure and tunnel are subject to the ground motion and response induced ground deformation.

The outcome of the longitudinal analysis provided the maximum axial and bending strain which are adopted to calculate the combined strain. These results of strain are considered with other load cases and combinations to design the concrete structures against ULS scenario. The results of transverse analyses represent the thrust forces and bending moment due to the earthquake event, which are adopted to combine with other load cases and combinations to determine the design of concrete structures to ensure the structural capacities of the buildings to resist earthquake events under service life cycle. Therefore, the results of closed form solutions evaluate the effect of seismic design on the performance of concrete structure. These outcomes undertaken based on two analyses determine the seismic demands from the earthquake event to evaluate the performance and behavior of concrete structures while it is considered with applicable when structures are subjected to combined seismic and static loads in accordance with the load factors and load combinations specified in the standards.

4. Conclusion

The seismic behavior of underground structures and frame structure buildings are required to be designed in accordance with the minimum design and reinforcement detailing requirement specified in the Standards. For the typical frame structure, the seismic design is based on the type of moment frame which is in relation to the levels of seismic risk and category. The seismic risk for concrete structures is classified into three critical categories, including low, moderate, and high.

The levels of intensities of earthquake events including MCE, MDE, ODE and OBE, are identified to evaluate the seismic design of concrete structures. The design of concrete structure against seismic loading is required to satisfy the serviceability and ultimate state of design requirements to ensure the performance and response of structures during MCE and MDE events. The analysis in accordance with the ODE and OBE design is not essential as these scenarios do not govern the components of the design.

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However, these design conditions provided the estimation of structural performance after earthquake event and determined the likelihood of levels of repair while damage is caused by ground movement and seismic activity.

The typical primary ground deformations and movements caused by seismic wave propagation are in accordance with three major strain conditions which are adopted to evaluate to determine the seismic response and behavior of concrete structures, including the longitudinal axial tension and compression forces, the longitudinal bending moment, and ovaling or racking of the structures and structural components.

The outcome of the longitudinal analysis in accordance with the closed solution indicated that the impact caused by earthquake events in plain and reinforced concrete structure is not extensive and critical while falling into part of the ULS and SLS design calculations. This adverse effect does not usually govern the design of structure. However, it is still critical to check the stability of the structure during and after extreme scenario and condition. Moreover, numerical modeling of similar problems is recommended in order to develop a comprehensive comparison between closed form solutions and numerical results, but the results are believed to be converged. Furthermore, the future investigation of relevant studies should be focusing on the post influence after an earthquake event, and to determine the safety reduction of structural stability under post seismic event which is possible to be adopted to evaluate whether the structure still meeting the design life and requirement intent.

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