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PRACTICAL SOLUTIONS TO UNDERGROUND STATION DESIGN – AN ENGINEER'S APPROACH

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ABSTRACT

In urban cities, underground tunnels and stations for rapid transit systems are commonly buried underground. Compared with cantilever above-grade structures, underground stations have performed relatively well in past earthquakes. This may be attributed to the unique service conditions of underground stations- lateral support by surrounding soils. Station designers need to consider the interaction with surrounding soils for earthquake loading.

Seismic design methods for underground stations are different from that of cantilever above-grade structures. Shear distortion is typically believed to be the major concern for underground structures. Three methods are discussed here: the dynamic earth pressure methods, the free-field racking deformation method and the soil-structure interaction methods. The advantages and disadvantages of these methods are compared and summarized.

Two models were employed in designing the Canada Line Stations in Vancouver, British Columbia, Canada. Both of the models originated from the dynamic earth pressure methods with the consideration of shear racking deformation. The first model assumes that dynamic earth pressure is transferred to the base by a moment frame consisting of walls and slabs. The whole structure is assumed to sit at the base. This model was for structures built in complicated soil condition, such as a station half-buried in the bedrock and half buried in the soft soil. In the second model, free-field racking deformation is used to check major structural members and joints first. Then the slabs and walls are designed to sustain the dynamic and static soil pressures. Moment redistribution at joints is considered to minimize the wall and slab thickness. All soil pressures are assumed to be transferred to the other side by slabs and resisted by the passive pressure. The concept of this model is to produce a flexible structure to move together with seismic shear wave. This model can produce more economical design than the first model. Both models were used in designing different stations.

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Introduction

In heavily populated urban cities, rapid transit systems are commonly built underground to save ground space for traffic and commercial use. The stations of the transit line systems sometimes locate under roads or other public-owned land. These underground stations serve as the exit for transit systems during extreme events, as well as the structural support to the loads from roads for ground traffic. Structural design of underground transit stations demands particular care and consideration for earthquake loading to produce a safe and affordable design. The methods and models discussed in this paper are based on the experience in designing several Canada Line stations in Vancouver, British Columbia, Canada.

Design Methods

Above-grade structures are typically cantilevered from the ground. They are commonly designed with designated energy dissipation systems, such as shear walls, moment frames and cross braces for severe earthquake loading. Compared with above-grade structures, underground stations have performed relatively well in past earthquakes. This may be attributed to the unique service conditions of stations –the lateral support from surrounding soils. However some severely damaged examples were also reported, as summarized by Youssef et al. (2001).

Limited literature survey does not produce much discussion particularly for the design of underground station structures. The methodologies for similar structures, such as underground bored tunnels and cut-and-cover tunnels can be used here (Wang 1993 and Youssef et al. 2001).

Dynamic earth pressure method

Two dynamic earth pressure methods, Mononobe- Okabe Method and Wood Method were summarized (Wang 1993). Both methods were developed for cantilever retaining walls. These methods assume that the wall can move and/or tilt to accommodate the movement of soil. The design seismic pressure is contributed by inertia force of the retained soil under the earthquake loading. Wood Method produces relatively higher design force than Mononobe-Okabe Method. Wood Method is particularly suitable for the design of sections of cut-and-cover tunnels with end walls, where the rigidity of end walls restrains the movement of side walls. Dynamic earth pressure methods are suitable for underground structures with shallow soil cover thickness. These methods require minimal parameters and are simple in calculation.

Free-field racking deformation method

Structural design of underground structures may have to consider different response, such as axial tension or compression, longitudinal bending and racking deformation. For station structures typically with limited length in the longitudinal direction, compression or bending in longitudinal direction can be justified not important. Racking deformation is the major concern.

Free-field racking deformation refers to ground distortion or strain without the structure being present. The free-field racking deformation varies with the distance to the bedrock.

Closed-form solutions of racking deformation for different types of waves can be obtained by assuming one-dimensional elastic wave propagation in homogeneous media. To accommodate the demand of racking deformation, the structure is expected to be flexible enough to distort with the surrounded soil. The flexibility of structures typically requires that: 1) the joints between walls and slabs are pin-connected or ductile enough; 2) the thickness of walls and slabs are not over-designed for static loads. Free-field racking deformation method is believed to be effective when the demand of ground distortion is small (Wang 1993).

The free-field racking deformation method applies to structures with their stiffness similar to the surrounded soil. The results are conservative for structures buried in soft soils, as heavy static loads in soft soils result a stiff structure which may deform less than the ground. This method is a simple and effective design tool when the seismically induced racking deformation is relatively small.

Soil-structure interaction methods

Some closed-form solutions for soil-structure interaction are available for deep buried circular tunnels. These solutions are typically based on the theory of elastic beam on elastic foundations. Such kind of closed-form solutions are not available for structures with a rectangular cross-section due to the geometric sensitivity.

Wang (1993) discussed some factors that contribute to the soil-structure interaction effect, including the relative stiffness between soil and structure, structural geometry, ground motions and soil embedment depth. A series of two-dimensional finite element analysis were carried out to study the relationship of these factors. The model is linear in general with the consideration of an energy absorbing boundary. With the results of finite element analysis, some empirical-based relationship between “racking coefficient” and “flexibility ratio” was established. The “racking coefficient” is similar to the “displacement amplification factor” for above-grade structures, with which a simplified frame analysis model can be employed to study the soil-structure interaction behaviour of underground tunnels (Wang 1993).

General Consideration

Due to limited space near Downtown Vancouver, the discussed stations were constructed by vertical excavation temporarily supported by mini-piles and structural frames. The vertical excavation provides the structure with direct contact with at-rest soil on the sides. The soil depth above the bedrock is less than 10 meters typically, except Yaletown Roundhouse Station, which locates near False Creek with a soil depth more than 30 meters.

The geometry of the stations is a box-type. A typical station consists of a base slab on the foundation, a roof slab supporting the soil and traffic loads on the top, one or several suspended slabs in the middle for service and some perimeter walls on sides. Columns are also used to support the roof slab and the middle slabs. The thickness of back-fill placed on the top of the roof slab ranges from 1 meter to 3 meters. The overall length of stations ranges from 55 meters to 90 meters. The width varies from 16 meters to 25 meters. The bottom of the station locates at a depth of 15 meters to 20 meters below the grade.

Among above-mentioned design methods, soil-structure interaction analysis with computer software does not appear to be practical in this case. Firstly, the structural configuration of stations is much more complicated than that of tunnels. The uniform cross-section of tunnels only requires two-dimensional soil-structure interaction analysis. However, stations have many end walls, interior walls and deep beams, all of which stiffen the perimeter walls. To account for the contribution of all structural elements, three-dimensional soil-structure interaction is necessary. Secondly, some stations have a bottom portion built in the bedrock and a top portion in soft soils. It is a challenging task, if not practically impossible, for engineers to efficiently model the interaction among soils, bedrocks and structures. Thirdly, the capability of existing software may be a bottleneck to accurately predict structural behaviour under an extreme event. For example, to account for the compressibility of loose soil and potential slip near rigid corner walls, the constitutive relationship of the soil should cover full range of three-dimensional nonlinear behaviour, including failure surface, post-failure behaviour and time effect. Soil-structure interaction analysis also makes it difficult to coordinate the collaboration and responsibility between the structural engineer and the geotechnical engineer.

Design Strategies

Lateral design of discussed stations is based on a geotechnical summary with basic geotechnical information, including static soil pressure, seismic soil pressure, structural drift and water table. The seismic soil pressure and drift is based on a typical section from preliminary structural layout. The provided seismic soil pressure profile is in inversed-triangular shape, which is probably calculated with one of the dynamic earth pressure methods. The structural drift is interpreted as the estimation of the free-field racking deformation.

With the provided geotechnical information, two different models were employed in analyzing and designing the stations. Both of these models are mainly based on the dynamic earth pressure methods. The requirement of shear racking deformation was also considered.

The first model originated from the design of traditional above-grade structures, in which the cross-section of stations is simplified as a moment frame above the base. In Fig.1, the dark lines represent the perimeter walls, the roof slab, the base slab and one intermediate slab. The seismic earth pressure profile is shown in inverse-triangular shape while static earth pressure and surcharge are not shown for clarity. The structure was assumed to sit on the bottom of the base slab and not to contact with soil on the sides. Moment resistant connections between perimeter walls and roof slab were assumed in order to resist seismic lateral force. The connections between perimeter walls and the base slab were assumed to be roller-supported, as the wall reinforcement at the joints was detailed so. Due to the consideration of catastrophic consequence of potential joint failure, the earthquake design force was calculated without any reduction from ductility factor (i.e., ductility factor of one). The strength design was based on the load combinations for the extreme level of earthquake hazard. Structural lateral drift was also calculated and checked against the requirement of racking deformation. This model can be applied to any section regardless of its stiffness, such as a wall section stiffened by an end wall. The model is believed to be useful for complicated soil conditions where the distortion of soil cannot be well-justified. This model was used in designing Olympic Village Station, of which the bottom portion is buried in sandstone and the top portion is surrounded by soft soil.

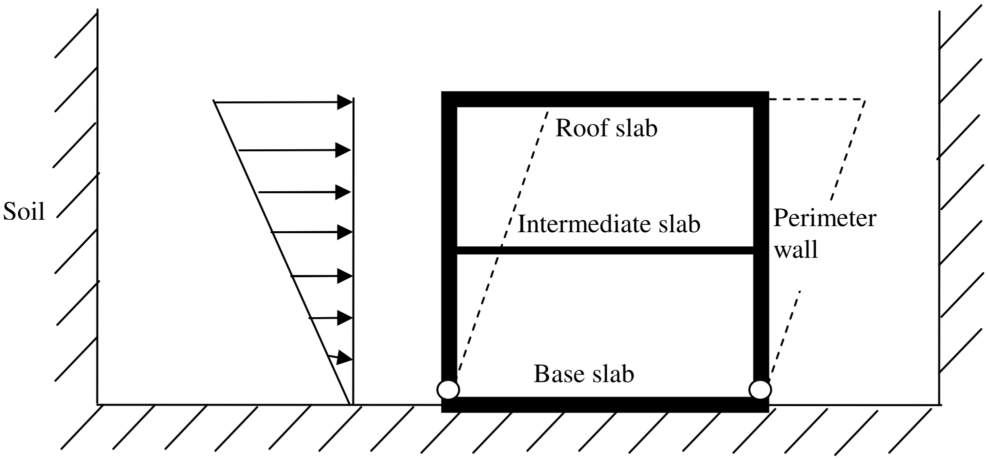

Fig. 1 Moment-frame model above the base slab

Another model combines the racking deformation method with the dynamic earth pressure method together (Fig. 2). First, racking deformation provided by the geotechnical summary was used to calculate the strain and internal forces of major structural members, such as the perimeter walls and roof slabs. It was found that the internal forces to achieve the design racking deformation are so small that they can be ignored in the design. Then the earthquake and static soil pressures were combined to size and reinforce the perimeter walls and slabs. To produce a flexible configuration to accommodate potential shear distortion greater than that of Maximum Design Earthquake (MDE), the walls and slabs were sized just enough for strength combinations, but not over-designed. The joints between slabs and walls were detailed to develop moment capacity, such that maximum allowable moment redistribution between walls and slabs can be achieved. Some damage, such as concrete spalling, was expected at joints under MDE.

In terms of the load path, all soil pressure applied to the wall on one side (left side in Fig. 2) is assumed to be transferred to the wall on the other side (right side in Fig. 2) by the diaphragm effect of slabs. The status of the earth pressure on the other side may be changed from active pressure to passive pressure. Although it is difficult to quantify its profile, the passive pressure is justified to vary depending on potential movement of the wall and locations of slabs. Generally speaking, the dynamic pressure is treated as instantaneous impact load generated by seismic elastic waves. Once the elastic wave propagates to the other side, the soil pressure on the other side is increased and thus restrains the section from further movement. As the whole structure is flexible, some extra integrity reinforcement was placed among intersections of structural elements such as intersections betweens all interior walls and slabs.

The concept of this model was implemented in designing Yaletown Roundhouse Station. The design based on this model is more economical than the first model.

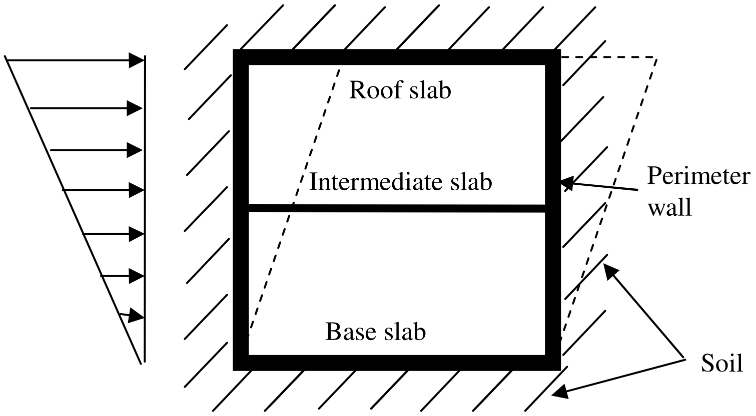

Fig. 2 "Flexible" frame placed against soil

Summary

Three types of design methods for underground structures were discussed here: the dynamic earth pressure methods, the free-field racking deformation method and the soil-structure interaction methods. The soil-structure interaction methods were believed to be not feasible in this case. Some practical consideration in designing some Canada Line Stations was presented. Two models, both of which originated from the dynamic earth pressure methods, were introduced. In the first model, the structural section is simplified as moment frame to transfer dynamic earth pressure to base. In the second model, the structure and its joints are checked against seismic racking deformation. The walls and slabs are designed to resist dynamic and static soil pressure, while lateral stability is assumed to be provided by the passive soil pressure. These two models were used in different stations.

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