A study of racking deformation for seismic response of rectangular underground structure

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Abstract— **Underground Substructure facilities are the important part of the modern society constructions. The use of underground facilities and infrastructures is the result of lack of space for those facilities above ground and the requirement of having that infrastructure below grade. For Example: Transportation facilities (subways, highways and railways), material storage, water supply and drainage etc. These substructure facilities built in earthquake prone areas must withstand both static and seismic (dynamic) loading. An effort has been made in the present study to find racking deformation of underground structure by analytical method. Seismic design loads for underground structures are defined in terms of the deformations and strains developed on the structure due to surrounding soil or due to the interaction between soil and the structure. The free-field analysis was carried out to find the ground deformation due to Dynamic load, and the substructure is designed to accommodate these deformations.**

Keywords— ***Soil-Structure Interaction, Free-field deformation, Flexibility ratio, Racking deformation., Displacement***

I. INTRODUCTION

The seismic response of an underground structure is different from the response of a superstructure founded on the ground surface. The confining action of surrounding soil media is the main reason for this difference. In simple words, while superstructures are free vibrating systems, underground structures deform compatibly with the surrounding soil stratum. This fact encourages many of researchers and engineers to pursue deformation-based studies in the seismic design of underground structures, since none of the available force-based methods have been developed to take into account the deformation compatibility. In many of the cases, seismic effects for box culverts and buried structures will not be considered except when they are subjected to unstable ground conditions (e.g., liquefaction, landslides, and fault displacements) or large ground deformations (e.g., in very soft ground).

The above statement uses significantly subjective and undefined terms such as “large ground deformations” or “very soft ground”. Most of the case studies have shown that soil profiles composed of medium dense or medium stiff layers may also experience large deformations, if they are subjected to strong ground motions having higher intensity. Also it is the engineer’s responsibility to check that the designed structure can satisfactorily resist the probable seismic excitations, as well as the service loads during its lifetime. Hence, it is strongly recommended to check seismic performances of underground structures in seismically active regions.

Many researchers have carried out the seismic performance evaluation of underground structures after a wide range of seismic events. Sharma and Judd et al., (1991)[1] performed a comprehensive study on damage patterns in buried structures and their findings reveals that underground structures are also vulnerable to seismically-induced failures and damages. Although they are considered to be seismically safe when designed for service loads, seismic performance of the underground structures should be checked especially for scenarios including high magnitude events and small overburden levels. Shallow tunnel, i.e. when overburden is less than 15 m, are usually designed as cut and cover structures and these structures are

more vulnerable to seismically-induced damages compared to deeper tunnels (Y.M.A. Hashash et al., 2001)[2]. As stated by Wang et al., 1993[4], as the depth of burial decreases:
(i) lower confinement action results from lower overburden pressure, and (ii) higher amount of displacement is observed. Moreover, these shallow buried structures are subjected to higher levels of forces owing to their higher rigidities (Y.M.A. Hashash et al., 2001)[2].

II.ANALYTICAL METHOD TO FIND RACKING DEFORMATION

Here the method developed by Wang et al., (1993)[4] and by Hashash et al., (2001)[2] is used to find the racking deformation of the structure. Basic data required in this analytical method are stated as below. The data is taken of 2015 Nepal Earthquake.

- Peak Magnitude of previous earthquakes at study site (M_w) = 7.8
- Peak ground particle acceleration at surface, (a_{max}) = 0.50g
- Apparent velocity of s-wave propagation in soil (C_m) = 750 m/sec.
- Density of soil (Stiff soil) = (ρ_m) = 2000 kg /m^3

Below are the structural parameters of the tunnel considered (Fig 1):

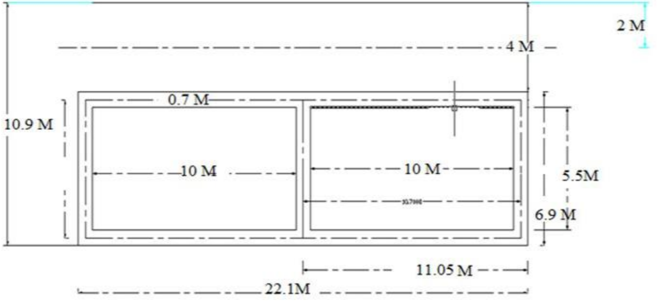


Fig. 1. Section Dimension

- Width of the station box (W) = 22.1 m.
- Height of the station box (H) = 6.9 m.
- Depth of soil layer to the top of station box (D) = 4 m.
- Per unit Length for the rectangular cross section was considered.

As per the collected earthquake data:

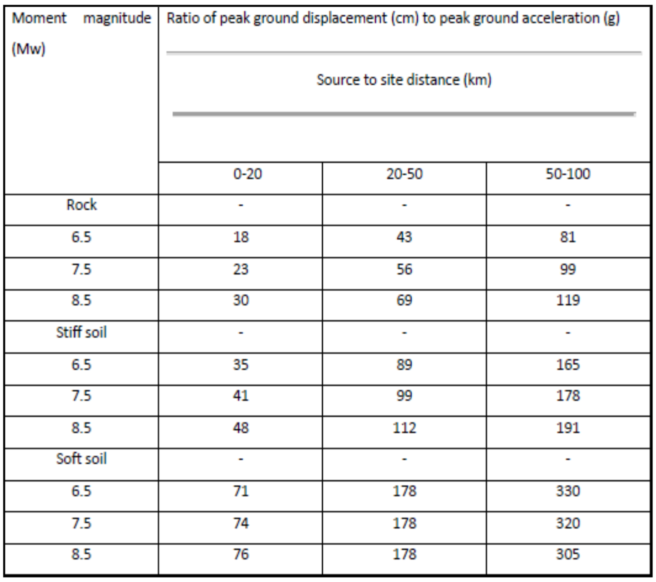
- The peak ground acceleration at the depth of tunnel (a_s) = (0.9 * a_{max}) = 0.9 * 0.5 = 0.45 g.
- 0.9 is the ratios of ground motion at depth to motion at ground surface obtained from Table 1.

Table 1: Ratios of ground motion at depth to motion at ground surface [Y M A Hashash et al., 2001)[2]

Tunnel Depth (m)	Ratio of ground motion at tunnel depth to motion at ground surface
≤ 6	1.0
6-15	0.9
15-30	0.8
>30	0.7

Assuming stiff soil medium, (Source to site distance = 59.9 km) peak ground velocity at the depth of tunnel can be calculated as,

- Peak ground velocity at the depth of tunnel = Vs = (k × a_s).
- From Fig 2, k = Ratio of peak ground displacement (cm) to peak ground acceleration (g), (corresponding to source to site distance) = 135.7 (cm/sec)/g.
- V_s = 135.7* 0.45 = 61.065 cm /sec = 0.611 m/sec



Moment magnitude (Mw)	Ratio of peak ground displacement (cm) to peak ground acceleration (g)		
	Source to site distance (km)		
	0-20	20-50	50-100
Rock	-	-	-
6.5	18	43	81
7.5	23	56	99
8.5	30	69	119
Stiff soil	-	-	-
6.5	35	89	165
7.5	41	99	178
8.5	48	112	191
Soft soil	-	-	-
6.5	71	178	330
7.5	74	178	320
8.5	76	178	305

Fig 2: Ratio between peak ground velocity to peak ground acceleration at the surface in rock and soil [Y.M.A. Hashash et al., 2001][2].

Maximum free-field shear strain at the elevation of tunnel = $\gamma_{max} = \frac{V_s}{C_s}$

C_s = Apparent velocity of s-wave propagation in soil

C_s= for rock = ≥ 750 m/sec

For stiff soil = 200-750 m/sec

For soft soil = < 200 m/sec.

γ_{max}= 0.611 / 750 = 0.00081467.

Free-field deformation = Δfree-field = γ_{max}* H = 0.00081467 * 6.8 = 0.0056212 m = 5.6212 mm

III. DETERMINATION OF FLEXIBILITY RATIO (FR)

$$(R_{rec}) = \left[\frac{4(1-\vartheta_m)}{\left(\frac{(3-4*\vartheta_m)}{F_r}\right)+1}\right]$$

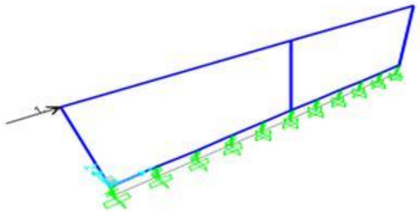


FIG. 3. UNIT FORCE APPLIED AT THE ROOF LEVEL

In assessing soil-structure interaction effects on underground structures it is usual to define flexibility ratio.

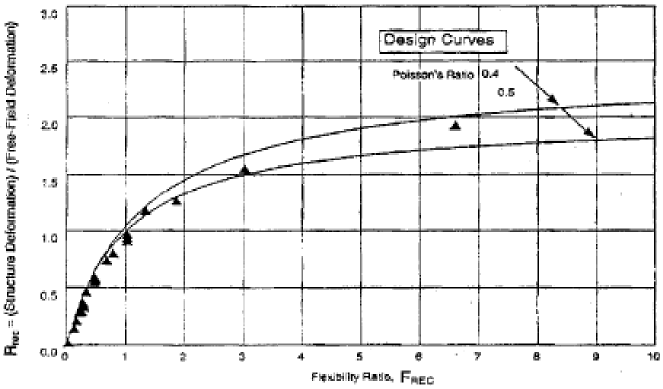
$$F_r = \frac{G_m \times W}{S_1 \times H}$$

In these expressions, the unit racking stiffness is simply the reciprocal of the lateral racking deflection,

$S_1 = \frac{1}{\Delta}$, caused by unit concentrated force, Fig 3.

Fig. 4 Racking ratio between structure and free-field [Wang et al., 1993][4]

For a rectangular frame with arbitrary configuration, the flexibility ratio can be determined by performing a simple frame analysis using a conventional frame analysis.



G_m = 1125000 KPa

S_1 = 476190.04 KPa

F_r = 7.567

Based on the Flexibility Ratio, the racking ratio can be calculated as:

From Fig. 4, the racking deformation of the structure is calculated as:

$(R_{rec}) * \Delta_{free - field}$ = 2.02529 * 5.6212 = 11.385 mm

IV. CONCLUSION

The following conclusion can be made from the above study:

- Peak Ground Acceleration (PGA) depends on soil properties (Soil density, Young's modulus of soil, Shear modulus, poison's ratio,).
- Computed Free-field deformation and Racking deformation using Analytical method were 5.6212mm and 11.385mm respectively.
- Deformation of structure during soil structure interaction was dependent on Flexibility ratio of the structure.

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