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RELATIVE MOVEMENTS FOR DESIGN OF COMMODITIES RUNNING BETWEEN TWO ADJACENT NUCLEAR SAFETY-RELATED STRUCTURES

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ABSTRACT

In nuclear power plants a large number of commodities such as piping, HVAC, conduits and cable trays communicate between adjacent buildings. Such commodities supported by two adjacent buildings can be subjected to significant relative movements due to settlement and seismic event. For plants where adjacent structures are seismically separated and not founded on a common base mat, unless adequate care is taken, the design of such commodities maybe based on significantly underestimated relative movements.

Relative movements due to building settlement may be significantly underestimated by neglecting the possible tilt of the structures. Relative movements due to seismic event maybe underestimated by considering only the calculated relative movements from seismic analysis of the two structures. Seismic analysis of the structures are performed either using fixed base analysis or soil-structure-interaction (SSI) analysis. In either case, the calculated movements from these seismic analyses do not account for any movement due to stability evaluations where passive soil pressure is considered to demonstrate stability against sliding and/or overturning. Furthermore, with certified designs for new generation of nuclear power plants, quite often the stability of the structure against overturning may utilize energy balance approach, which includes some tilting of the structure.

The purpose of this paper is to discuss the above issues in depth and provide the readers suggestions and/or recommendations on how the design can appropriately account for such relative movements. In addition, since there is no current industry guidance on how to combine these relative movements, this paper presents a new formulation for combining applicable relative movements.

INTRODUCTION

In order for Structures, Systems, and Components (SSC) to perform their intended safety function throughout a 60-year life of a nuclear power plant, relative building movements need to be accurately estimated and reflected in design. Commodities supported on two adjacent structures and running between them may undergo significant relative movements due to settlements and seismic event. While the effect of tilt may be less severe in the case of two buildings found on a common foundation, it can be significantly pronounced if the two structures do not share a common base mat. Due to seismic excitation, two adjacent structures may respond differently depending on each structure's mass and stiffness characteristics, which if out-of-phase, can lead to undesirable results for supported commodities. Therefore, it is important to understand and account for all possible movements any two adjacent structures with safety-related commodities running between them may undergo during the plant life.

Figures 1 and 2 below provide a visualization of the effect of tilt on adjacent structures with commodities communicating between them.

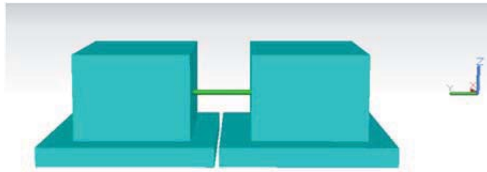

Figure 1: Two adjacent structures with commodities running between them with no tilt.

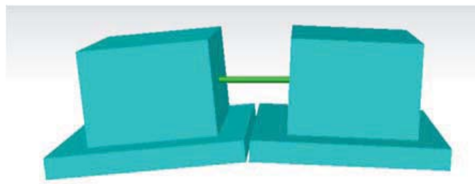

Figure 2: Two adjacent structures with commodities running between them with tilt.

CODE PROVISIONS / GUIDANCE

No comprehensive guidance is available in the existing building codes for determination of relative movements for design of commodities supported by two adjacent structures. The available guidance is generally limited to seismic separation. Although it is not provided for comparison purposes, two codes are being referred to here for providing guidance on building separation; these are the International Building Code (IBC), IBC (2009), and the American Society of Civil Engineers (ASCE), ASCE 43 (2005).

Table 1: Code provisions for building separation.

IBC (2009)	ASCE 43 (2005)
$\delta_{MT} = \sqrt{\delta_{M1}{}^2 + \delta_{M2}{}^2}$	$\delta = 2\sqrt{\delta_1{}^2 + \delta_2{}^2}$
$\delta_{M1}, \delta_{M2} =$ Max inelastic displ	$\delta_1, \delta_2 =$ Max elastic displ

It is noted that the relative displacements mentioned in IBC (2009) and ASCE 43 (2005), which are used as guidance for building separation, are only due to seismic loads and there is no mention of displacements due to settlements and tilts of structures or those from stability evaluations. The IBC (2009) equation combines seismic movements based on inelastic displacements, whereas the ASCE 43 (2005) for the nuclear code combines the movements based on elastic displacements multiplied by a factor of “2”. The “2” factor is included in the ASCE 43 (2005) equation to provide less than 10% chance of significant impact between adjacent structures for an input ground motion of 1.5 times the Design Basis Earthquake (DBE). The factor was conservatively selected in lieu of requiring multiple non-linear time-history evaluations of adjacent structures for an input ground motion of 1.5 times the DBE.

δ_{M1} and δ_{M2} in the IBC (2009) equation in Table 1 are maximum inelastic response displacements of adjacent buildings as follows:

$$\delta_M = \frac{C_d * \delta_{max}}{I}$$

Where,

C_d = Deflection amplification factor per Table 12.2-1 of ASCE 7 (2005), which depends on the ductility of the lateral load resisting system.
δ_{max} = Maximum elastic displacement per Section 12.8.4.3 of ASCE 7 (2005).
I = Importance factor per Section 11.5.1 of ASCE 7 (2005), which depends on the occupancy category (I, II, III, or IV). For nuclear power plants the occupancy category is IV.
As noted the above guidance does not account for components other than seismic.

APPLICABLE BUILDING MOVEMENTS

In order to accomplish a safe design, commodities running between two adjacent buildings have to accommodate all applicable building movements throughout the life of a plant. The following sections describe applicable building movements for design of such commodities.

Movements Due to Differential Settlements and Tilts

Total relative movements can be significantly underestimated if relative movements as a result of differential settlements and tilts are not accounted for in design. Effects of short term and long term settlements need to be addressed in design.

Construction sequence can play a significant role on the differential settlement and tilt of two adjacent structures. As the construction at the site progresses, differential settlements and tilts of the structures and thereby the relative movements between the adjacent structures change. Such changes can be very significant, for example, two adjacent structures that at some point in time tilt toward each other may tilt away from each other at a later time.

An important consideration to keep in mind during design is the location of penetrations on the elevation of the outer walls of the two adjacent structures. These penetrations serve as a passage of commodities that run between the two adjacent structures. The higher the point of passage on the elevation of the building, the more the angular distortion due to tilt and therefore, the more movements that needs to be accounted for.

When calculating differential settlements and tilts, use of available commercial software is recommended. Using such software capable of considering construction sequence and three-dimensional modelling, three-dimensional Finite Element Models (FEM) can be constructed to calculate differential settlements and tilts with due consideration to construction sequence and activities such as watering and dewatering of the site. Also the knowledge gained from such analyses can be used to determine the optimum time for connection of commodities running between two adjacent structures to minimize the relative movement that has to be accommodated.

Movements From Seismic Analysis

Individual building movements from SSI can be calculated using available commercial software. These displacements are usually calculated relative to free field motion at grade level. Since the free field motion with respect to all structures considered in design is the same, it can be used as a reference in calculating the maximum relative displacement of two points on two adjacent buildings. In the case of long underground tunnels, displacements along the tunnel due to traveling seismic wave effect need to be accounted for, which can be combined with the results from SSI analysis using the Square Root of the Sum of the Squares (SRSS) method.

It is noted that regardless of the type of seismic analysis being performed, i.e., whether it is performed using a fixed base approach or a SSI approach, the calculated movements from the seismic analyses do not account for any movement due to stability evaluations where quite often passive soil pressure is considered to demonstrate stability against sliding and/or overturning.

Movements From Stability Evaluation against Seismic Sliding

In order to demonstrate stability of the structure under consideration against seismic sliding the Factor of Safety (FOS) is calculated based on the ratio of the resisting force to the driving force. If passive earth pressure particularly full passive pressure is mobilized to resist sliding there will be significant movement due to sliding, which needs to be accounted for in design. Load-deflection curves can be constructed from literature such as, Cole and Rollins (2006), to estimate the amount of displacement required to reach various levels of passive earth pressure. A sample load-deflection curve is shown in Figure 3 below.

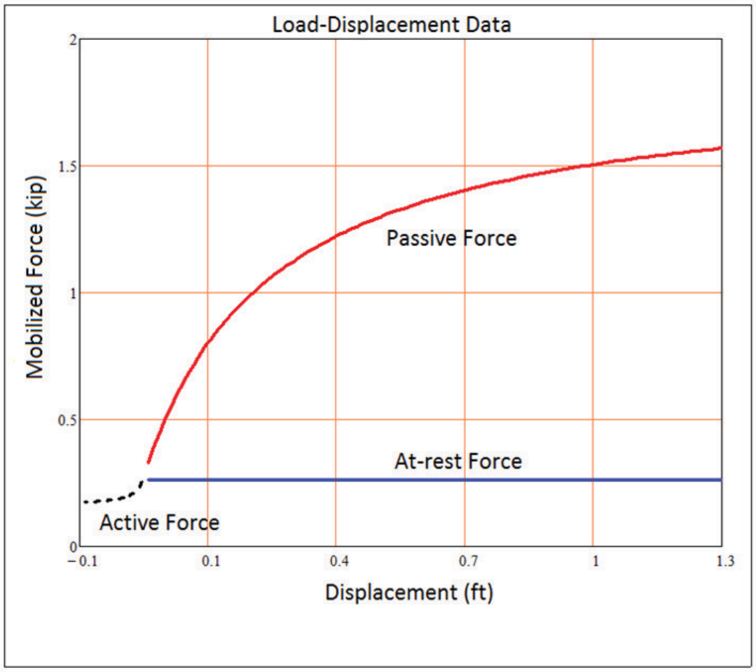

Figure 3: Sample Load-deflection curve constructed per Cole and Rollins (2006).

Seismic sliding movements can be also calculated utilizing sophisticated non-linear FEM analyses that are more realistic but can be costly due to time and effort involved. From such analyses, displacement time histories for various locations of each structure can be extracted. Figures 4 and 5 below show plots of displacement time histories for foundations of two adjacent buildings, which have commodities running between them.

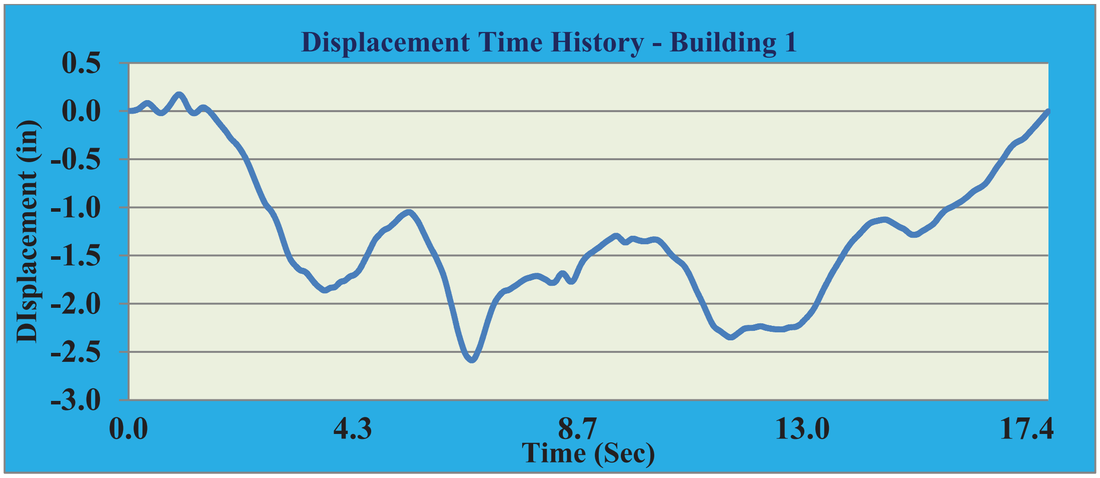

Figure 4: Displacement Time History for Building 1.

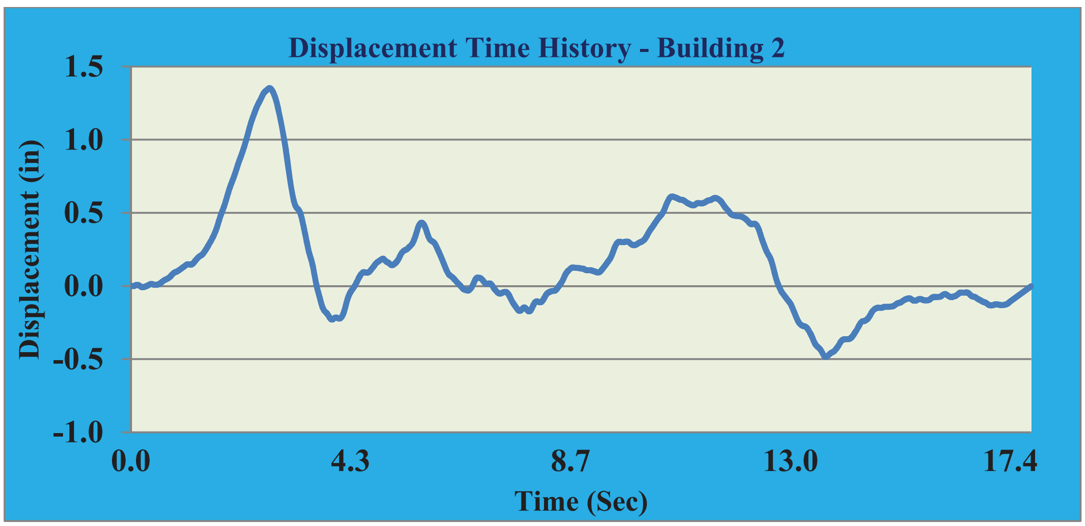

Figure 5: Displacement Time History for Building 2.

Once the individual displacement time histories for two points are extracted, relative displacements between the two points can be calculated as the algebraic difference between the two sets of time histories at every time step of the input motion. The maximum relative displacement from sliding stability evaluation for design of commodities can then be calculated as the maximum difference of all time steps.

Movements From Stability Evaluation against Seismic Overturning

The conventional method for stability evaluation against seismic overturning is to determine the FOS based on the ratio of the resisting moment to the driving moment considering the applicable loads as shown in Figure 6. For structures found stable against overturning using the conventional method, the structure will experience no uplift and therefore, no need to consider any additional movements

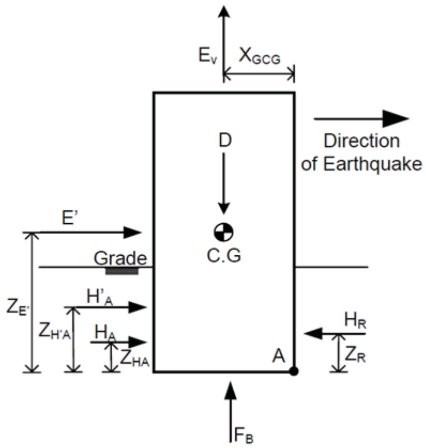

Figure 6: FBD of a building with Forces acting to overturn it about Point "A".

D – Dead load of the structure
F_B – Buoyant force
X_{GCG} – Horizontal distance from the geometric centre of the structure to edge of rotation
H_R – Resistance from soil pressure
Z_R – Moment arm for H_R
H_A – Lateral force from active soil pressure
Z_{HA} – Moment arm for H_A
$H`_A$ – Lateral soil force (seismic increment only)
$Z_{H`A}$ – Moment arm for $H`_A$
$E`_V$ – Vertical force from seismic excitation
E` - Horizontal force from seismic excitation
$Z_{E`}$ - Moment arm for E`
A – Origin of rotation for overturning

However, for structures where using the conventional method, the structure is unstable (i.e., FOS < 1), the structure will uplift and stability evaluation will require use of energy balance method. Use of energy balance method is quite common for certified designs for new generation of nuclear power plants with high seismic design spectra. In this approach two cases may be investigated as follows:

- Equilibrium Case: The equilibrium case is determined by the angle of rotation for which the potential energy of the structure equals the net work performed by all applied loads on the structure. The FOS for this case is 1.0. Since the angle of rotation for this case is relatively small the at-rest soil pressure is usually used as the resisting force.
- Limiting State: The limiting state is determined by the angle of rotation for which the Centre of Gravity (CG) of the structure resides directly above the exterior edge of the structure. Since the angle of rotation required to reach the limiting state is large, the result is a very large displacement and usually a very large FOS against overturning. However, such a calculated safety factor is misleading since under limiting case commodities within the structure and running between the adjacent structures may fail prior to reaching the limit state of the structure.

The angle of rotation calculated for equilibrium case can be used to determine the additional horizontal and vertical movements at various points of the structure. As mentioned previously, the higher the location of connection of commodities running between two adjacent buildings the more significant the maximum relative horizontal and vertical displacements can be.

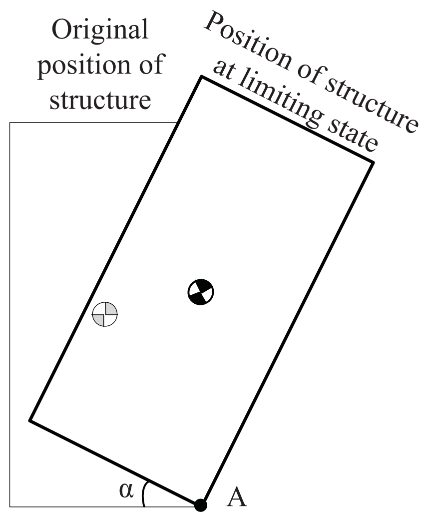

Figure 7: Limiting State for Overturning about Point "A"

TOTAL COMBINED RELATIVE MOVEMENTS

In order for commodities running between two adjacent structures to perform their intended safety function they have to accommodate the maximum relative movements their supporting structures will undergo throughout the life of the plant. Based on preceding discussions, proper design of such commodities will have to account for the following:

- Movements due to differential settlements and tilts
- Movements from seismic SSI
- Movements from stability evaluations against seismic sliding
- Movements from stability evaluations against seismic overturning

Since a seismic event may occur at any point in the plant life, accounting for the maximum relative displacements due to differential settlements and tilts will need to be considered and combined with seismic movements including those from stability evaluations. Review of current building and nuclear codes reveals no guidance on combining relative building movements. Therefore, the recommended formulations below aim at combining all applicable relative building movements for design of commodities running between adjacent structures.

$$MOV_{Commodity\ Design} = F * MOV_{settlement} + MOV_{seismic_{struct_1}} + MOV_{seismic_{struct_2}} \quad (1)$$

Where,

$MOV_{Commodity\ Design}$= Relative movement for commodity design

F = 1.5 = Factor to account for uncertainties in calculating differential settlements and tilts

$MOV_{settlement}$= Differential movement due to differential settlements and tilts

$$MOV_{seismic_{struct_1}} = MOV_{SSI_{struct_1}} + [MOV_{sliding_{struct_1}}{}^2 + MOV_{overturning_{struct_1}}{}^2]^{1/2} \quad (2)$$

$$MOV_{seismic_{struct_2}} = MOV_{SSI_{struct_2}} + [MOV_{sliding_{struct_2}}{}^2 + MOV_{overturning_{struct_2}}{}^2]^{1/2} \quad (3)$$

MOV_{SSI}= Movement from SSI analysis of each structure

$MOV_{sliding}$= Movement from sliding stability evaluation of each structure

$MOV_{overturning}$= Movement from overturning stability evaluation of each structure

CONCLUSION

In order for safety-related commodities, such as piping, HVAC, conduits, and cable trays, which are running between adjacent buildings, to perform their intended safety function throughout a 60-year life of a nuclear power plant, all applicable relative movements need to be accurately estimated and reflected in design. Commodities supported on two adjacent structures and running between them may undergo significant relative movements due to settlements and seismic event. For plants where adjacent structures are seismically separated and not founded on a common base mat, unless all possible movements are accounted for, the design of such commodities maybe based on significantly underestimated relative movements. Since current building and nuclear codes have no guidance on combining various relative movements of adjacent structures, this paper presented a formulation to account for and combine all applicable relative movements due to differential settlements and tilts, seismic SSI, and movements due to stability evaluations against seismic sliding and overturning.

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