Secondary response analysis of wall mounted equipment –Wairau Road 220kV GIS Building

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ABSTRACT: AECOM New Zealand Ltd. was the designer of a new Gas Insulated Switchgear (GIS) building at the existing Wairau Road Substation. One of the main tasks was to generate the response spectrum curves for the GIS Bus ducts' fixing points. A 3D Finite Element model was developed and a series of linear and non-linear Time History Analyses were performed following two different approaches. This paper summarises the findings of this exercise. The results showed that the introduction of soil-structure interaction did not have a significant effect on the response of wall mounted equipment. It was also concluded that the Time History Analysis method proposed by NZS1170.5 results in conservative responses when the non-linear effects of soil-structure interaction were taken into account. The study showed that the analysis based spectra were the governing design criteria when the NZS1170 approach was adopted.

1 INTRODUCTION

AECOM New Zealand Ltd. was commissioned by Transpower NZ Ltd to design a new 220kV Grid Exit Point (GXP) at Wairau Road Substation, Auckland. This new GXP would include a building to house Gas Insulated Switchgear (GIS) and would be referred to as the GIS Building. A key component of the design was to determine secondary response spectra (SRS) for the GIS Bus ducts fixing points. This information would then be used by the GIS equipment manufacturer to design the fixings and supports.

This paper focuses on the approach AECOM took to model and analyse the GIS Building and report on the response spectra for the points of interest for wall mounted bus ducts. The results for floor fixed equipment were discussed in another paper (Javadian 2012).

In section 2 the concept of the secondary response analysis and the previous research work in this field are briefly reviewed. Section 3 gives an overview of the project describing the building structure and equipment that were the subjects of the SRS analysis. The standards and software package used and assumptions considered for this exercise are also listed in this section. Section 4 provides an insight to the modelling and analysis methodology. In this section it is also explained how and why the analysis approach evolved over the course of the project. The results and findings of this study are discussed in section 5 with some of the results presented in graphical form. Finally, section 6 summarises the findings of this exercise and notes the opportunities for further research that are triggered by this study.

2 BACKGROUND

The development of numerical methods to evaluate the seismic performance of the Secondary Systems that are anchored to the Primary Structural System, such as equipment and building facilities, has been the subject of many academic publications for the past few decades (Sackman & Kelly 1979, Chen & Chen 1979, Singh & Suarez 1987, Peters et al. 1977).

There are two main approaches which provide the basis for engineering analysis and response calculations for secondary systems. These being, (a) the conventional response spectrum approach where the response behaviour of the primary structural system at the support points of a secondary system is determined initially while ignoring the effect of the secondary structure, and (b) the combined primary-secondary (PS-system) approach in which the secondary systems are considered as an integral part of the primary-secondary structural system. (Chen & Soong 1988).

3 PROJECT OVERVIEW

3.1 Building

The Wairau Road Substation GIS Building is a two storey (basement and equipment floor) concrete frame structure with reinforced concrete precast panel exterior walls forming the main lateral resisting system of the building. The 200mm thick precast panels are fixed to the concrete framing using cast in place stitch joints that are designed to act continuously on three sides of the panels.

The building floor area is approximately 220m^2 (20m long x 11m wide) with a lightweight steel roof supported on steel I-beams. The floors are cast in-situ reinforced concrete slab. The total height of the building is approximately 14m. A 140m^2 (20m long x 7m wide) Control Building with a total height of 7.5m (3m high basement under the main floor) and similar construction detail is attached to the North West side of the GIS Building. Figure 1 shows North East wall elevation of the GIS and Control Buildings. Due to the variable nature of the ground, the structure is supported on 16 reinforced concrete piles (bored) with variable lengths.

3.2 Bus ducts

A bus duct is an enclosed metal unit containing copper or aluminium busbars for distribution of large amounts of power between components of the distribution system (McGraw-Hill 2003). From the GIS Building three sets of bus ducts pass through the North East wall of the building to conduct the current from the GIS switchgear to the outdoor power transformer. Figure 2 shows the GIS floor plan with approximate locations of bus ducts.

Based on the information received from the manufacturer, the bus ducts weighed about 5.1 kN and were fixed to the precast panels using a steel angle frame along the underside of the wall opening. The natural frequency of the bus ducts was in the range of 10-20 Hz with a 2% damping ratio. This is the damping level that the results are reported for.

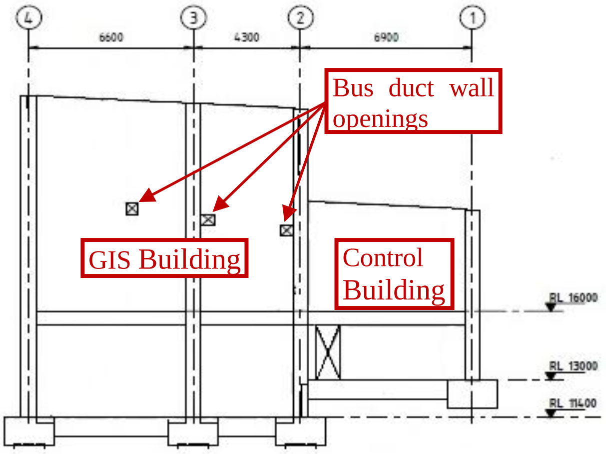

Figure 1: NE building wall elevation. Note the three openings for the bus ducts.

3.3 Standards and guidelines

The basis for design of equipment supports is provided by IEEE 693; Recommended Practice for Seismic Design of Substations. The procedures of NZS1170.5 were used for performing Time History

Analysis (THA), selecting suitable earthquake records and scaling them to the relevant design spectrum. ASCE 7-10 was referred to for an alternative THA approach. NZS3101:2006 was referred to for definition of reinforced concrete cracked section properties.

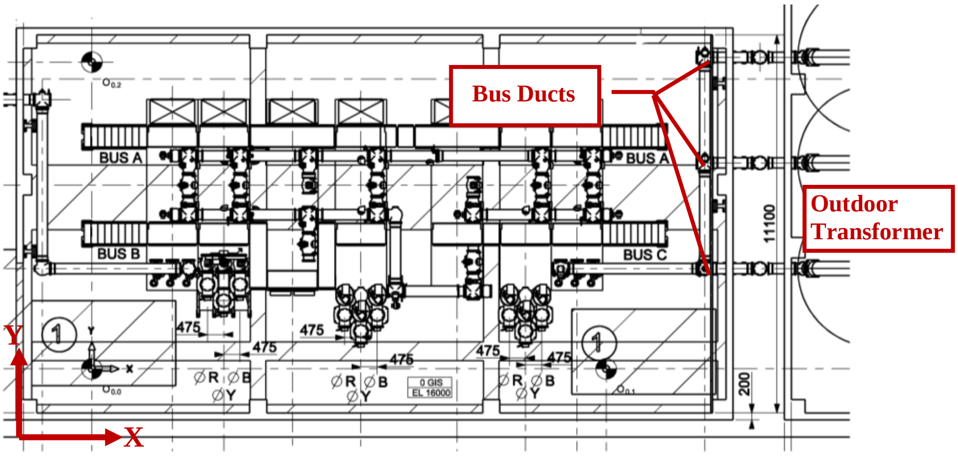

Figure 2: GIS Building floor plan with three bus ducts entering the building on the right. Note the X-Y directions.

3.4 Software

SAP2000 is a well-recognised and robust finite element computational framework that can perform THA and generate response spectrum curves for selected points in the model.

3.5 Assumptions

The building is assumed to have a design life of 50 years, an Importance Level of 4 and a ductility factor of 1.25 that corresponds to nominally ductile structures based on NZS 1170.5 definition. It is founded on Subsoil Class C, shallow soil. The low amplitude natural period for these sites is less than or equal to 0.6 Sec or the soil depths do not exceed the values listed in table 3.2 NZS 1170.5. The hazard factor considered for this site is Z=0.09 based on a site specific hazard report undertaken for another Transpower site in Auckland.

4 METHODOLOGY

For this exercise AECOM followed a conventional response approach described in section 2, however, consideration was given to equipment mass and location of centre of gravity in the primary model. Based on this approach the broad methodology was to build a 3D model of the GIS Building using SAP2000 computational framework, then introduce scaled earthquake records to the model and run THA. It would have been ideal to report the results at every fixing point, however, due to the time constraints, three fixing points were selected, one for each bus duct.

The 2% damped Pseudo Acceleration (PSA) response spectra were generated for these points and compared with 2% damped High Required Response Spectrum proposed by IEEE 693 (Fig. 3) over the frequency of interest (10-20Hz). IEEE recommends a reduction factor of 0.8 in the vertical direction that has only been applied to the IEEE design spectrum and not to the analysis results. The maximum responses for bus ducts were reported in graph form. The final design spectrum was an envelope of the maximum response from the model and the IEEE 2% damped design spectrum.

4.1 Model geometry

A 3D finite element model was developed based on the input from architectural drawings and the equipment manufacturer. The mass of each bus duct was equally divided between its fixing points and applied to the model as lumped transitional masses in three principal directions, X, Y and Z (Fig. 2).

When the modelling process started there was limited information available about the actual geotechnical conditions around the individual piles. It was therefore decided to model the building without the piled foundations with pin supports at column locations. Once the ground investigations were complete, the piles were added to the model with soil properties modelled as non-linear springs along the length of the pile in horizontal directions. A vertical restraint was introduced to the bottom of the piles.

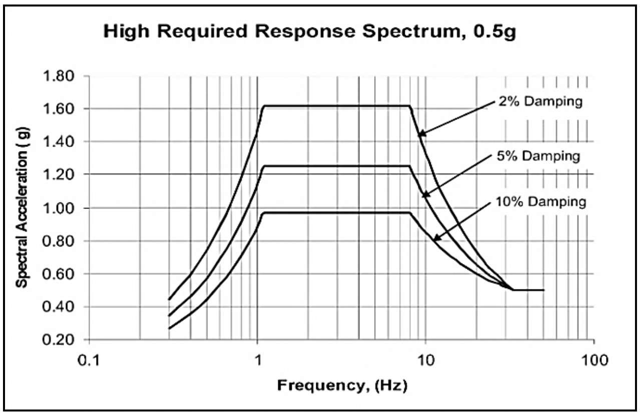

Figure 3: IEEE 693 proposed design spectrum for substation equipment

The information for pile p-y curves were provided by the Geotechnical Engineer for different pile depths at 0.5m intervals. Figure 5 shows a p-y curve generated based on the tabulated data at 19.5m depth. The AllPile programme was used to analyse the piles for lateral loading and generate the p-y curves (CivilTech 2011). AllPile uses COM624S calculation methods for lateral analysis (Wang 1993). For each set of applied boundary loads the programme performs an iterative solution which satisfies static equilibrium and achieves an acceptable compatibility between force and deflection (p and y) in every element (CivilTech 2011).

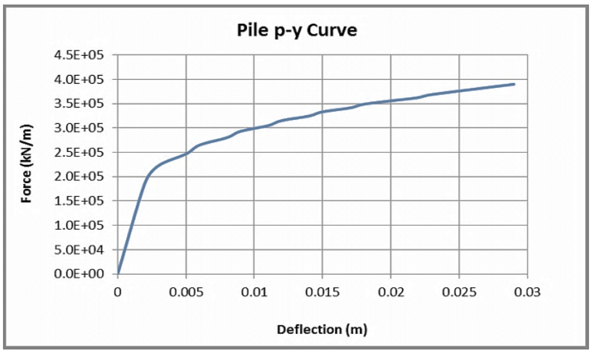

Figure 4: Sample P-Y curve for a pile at 19.5m depth

As the earthquake records were scaled to NZS1170.5 Ultimate Limit State (ULS) design spectrum, the stiffness of beam, column, wall and floor sections were reduced following the guidelines of the NZS 3101:2006 Table C6.6 to allow for cracking at this high level of loading.

4.2 **Modal analysis**

Prior to any dynamic analysis, a modal analysis is required to determine the number of modes to be included in the dynamic THA. An adequate number of modes was to be considered so that a mass participation factor of minimum 90% was achieved in all three principal directions. A number of iterations were required to establish this number.

A modal damping of 5% across all modes was assumed for this analysis. Although soil-structure interaction affects the damping properties of the soil-structure system, it was considered by the design team that a 5% damping ratio for the analysis of the soil-structure system is a conservative and practical design approach. A more accurate approach may be obtained with semi-space modelling with non-linear material that involves complicated boundary conditions in terms of stiffness, damping and cyclic rules that are still not at a design practical level (Conte et al. 2002).

4.3 Initial approach based on NZS1170.5 methodology

Initially, before the introduction of the piles, the NZS1170.5 approach was adopted for the analysis. Based on this approach the envelope of results from three earthquake records should be used for the design.

Three earthquake records suitable for the site characteristics were selected. The scaling procedure proposed by NZS1170.5 was followed to determine the Primary and Secondary components of the records and also factors k_1 and k_2. The 5% damped design spectrum proposed by NZS1170.5 for subsoil class C, and a 1 in 2500 year event was the target of this scaling process. Figure 5 shows the scaled spectra from the three earthquake records in comparison with the target spectrum. Table 1 summarises the earthquakes and their scaling factors. The envelope of the results from these three earthquake records was reported at each selected point and compared to the IEEE 693 design spectrum (refer section 5 for results).

The scaling process proposed by NZS1170.5 truncates at $0.4T_1$ where T_1=0.4 sec. This means that the scale factors are calculated ignoring the spectral values below 0.16 sec. The aim of the scaling is to ensure that for each given period, at least one of the earthquakes has a spectral value equal, or greater than the design spectrum. However, as the lower periods are ignored, if there is a spectral peak in the lower period range it will be magnified even more. Figure 5 shows this clearly with the dominant record (Imperial Valley) having a peak around 0.13sec that has been ignored in the scaling process.

Table 1: Summary of the earthquake records and scaling factors

Earthquake	k_1	k_2
Imperial Valley, California October 1979	0.65	1.26
Kalamata, Greece September 1986	0.5	1.26
Edgecumbe, Bay of Plenty New Zealand March 1987	0.5	1.26

The introduction of the soil-structure interaction resulted in a significant increase in the floor equipment response values, well above the normal design actions proposed by IEEE 693 (Javadian 2012). Due to design implications, a second approach was explored and adopted as discussed in the following sections.

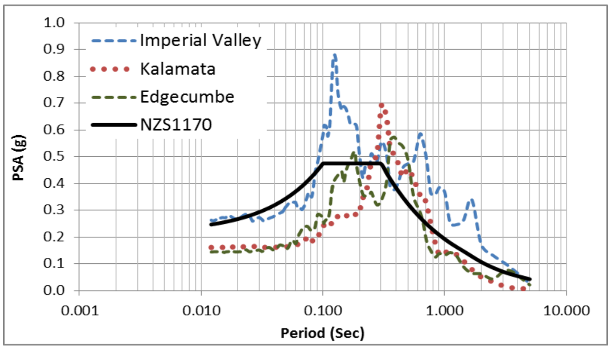

Figure 5: Scaled earthquake records and 5% damped NZS 1170.5 design spectrum, 1 in 2500 year event.

4.4 Revised approach based on ASCE7-10 methodology

An alternative common THA approach that is accepted by other international standards such as ASCE7-10 suggests using the average results of a minimum seven earthquake records. This approach was discussed with industry experts and was deemed to be acceptable for this exercise. Four additional suitable earthquake records were then added to the initial three to make a total of seven. Similar scaling processes were followed for these earthquakes. Table 2 summarises the added four earthquakes and their corresponding scaling factors.

Table 2: Summary of the additional earthquake records and their scaling factors

Earthquake	k_1	k_2
Imperial Valley, Compuertas, California October 1979	1.0	1.09
Kobe, Japan January 1995	0.5	1.09
Weber, New Zealand May 1990	0.95	1.09
Victoria, Mexico June 1980	1.0	1.09

5 RESULTS

Although the comparison between the NZS1170.5 method and the ASCE7 method is valuable, the results from these two approaches are reported separately for coherence purposes. It is evident that the ASCE7 method reduces the maximum response by a minimum of about 30% in all three directions (with maximum 65% in the Y direction). The introduction of soil-structure interaction has less impact on the wall mounted equipment in comparison to floor mounted equipment (Javadian 2012). However, this might be due to the small mass of the bus ducts and needs further investigation.

As mentioned in section 4.2, the influence of soil-structure interaction on the overall damping of the structure has not been taken into account in this study as it typically implies non-practical semi-space analysis for a reasonably accurate modelling (Conte et al. 2002, Zhang et al. 2004).

5.1 Initial approach based on NZS1170.5 methodology

Figures 6 to 8 summarise the maximum responses at the bus ducts fixing points in three main directions using the NZS1170.5 approach. It can be seen that the introduction of soil-structure interaction has slightly increased the response in both horizontal directions. However, the response in vertical direction sees a slight decrease and frequency shift. Over the frequency of interest, analysis based response spectra are generally the governing design criteria in all three principal directions.

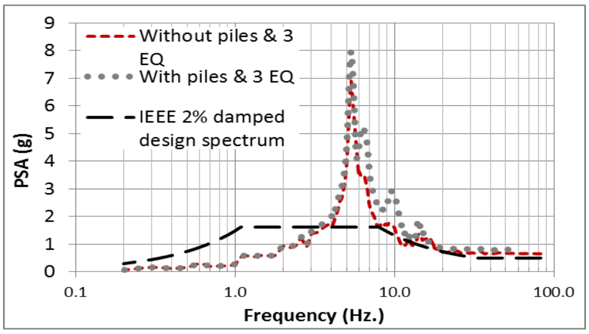

Figure 6: Bus duct maximum response in X direction

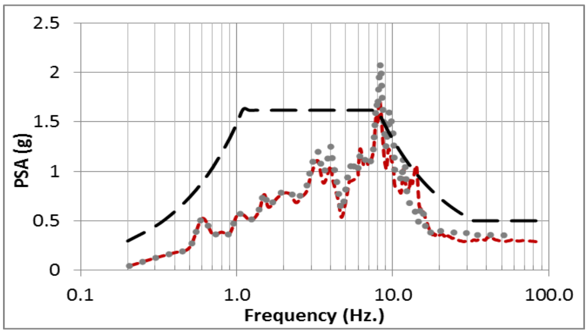

Figure 7: Bus duct maximum response in Y direction

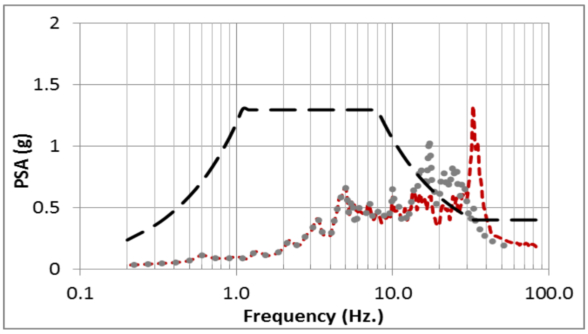

Figure 8: Bus duct maximum response in Z direction

NZS1170.5, in its section 8, proposes a simplified approach for calculating the seismic response of parts and portions. Based on this approach, the expected response for bus ducts is in order of 1.5g in both horizontal directions. From figures 6 and 7 it can be seen that the response from THA corresponds to these values over the frequencies of interest (10-20Hz) especially in out of plane direction (X). This correspondence is stronger when the soil-structure interaction is taken into account. The comparison of the vertical response is not that straight forward and is not considered at this stage.

5.2 Revised approach based on ASCE7-10 methodology

An additional set of results were generated using the THA method proposed by ASCE7 for the same fixing points. The maximum responses of the bus ducts fixing points are presented in Figures 9 to 11. Similar to the NZS1170 method, the introduction of soil-structure interaction slightly increased the maximum responses, but this time in all three main directions. Using this approach, over the frequency of interest, the IEEE spectrum is the governing design criteria in the Y and Z directions, whereas the analysis based response is the governing factor in the X direction.

Similar to NZS1170, ASCE7-10 proposes a simplified method for calculating the seismic response of the components (Chapter 13). Based on this method a maximum response of 1.0g in horizontal directions is expected. The response in X direction (out of plane) agrees with this simplified method for both models; however, in in-plane direction, the ASCE simplified method is overestimating the response of the bus duct. The comparison of the vertical response is not that straight forward and is not considered at this stage.

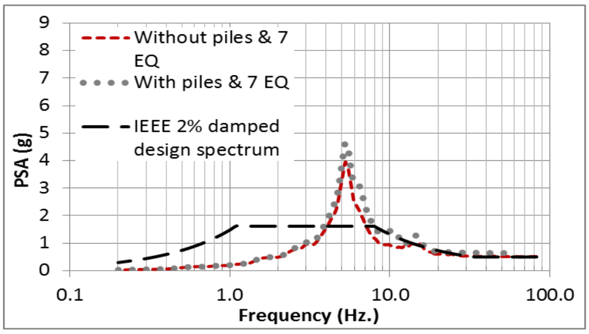

Figure 9: Bus duct maximum response in X direction

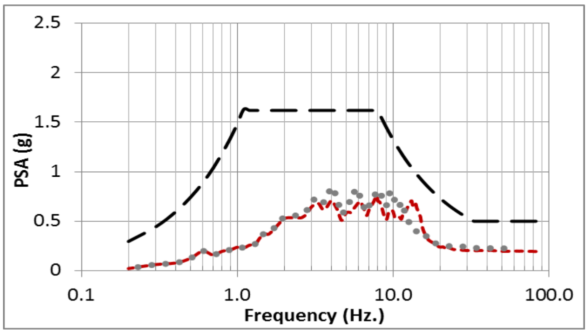

Figure 10: Bus duct maximum response in Y direction

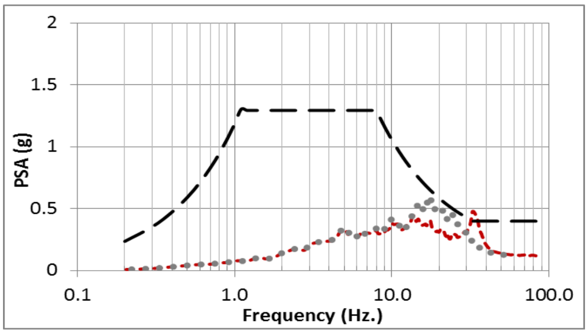

Figure 11: Bus duct maximum response in Z direction

6 CONCLUSIONS

Based on this study and the results and discussions presented in this paper, the following conclusions can be made:

1. The secondary response of bus ducts is not sensitive to the soil-structure interaction.
2. The Time History Analysis approach proposed by NZS1170.5 is conservative in comparison with ASCE 7-10 approach.

3. The equipment fixing design is governed by analysis generated response spectra when NZS1170 approach is adopted. Using ASCE 7-10 approach, the design is governed by IEEE spectrum except in X direction.
4. The simplified methods proposed by NZS1170.5 and ASCE 7-10 both give a good indication of response in out of plane direction (X) especially when the soil-structure effects are taken into account.

This study was a project specific assignment. It was however an ideal opportunity to use the theoretical substance for a practical cause. Furthermore, there are aspects of this assignment that could be improved or be the basis for further research. For example;

1. The corrected damping values when consideration is given to soil-structure interaction.
2. Replacement of the vertical restraint at the bottom of the piles with nonlinear elements that model the pile skin friction and end bearing in a more realistic way.
3. The effects of pile strain softening
4. With the advancement of the tools that are able to perform non-linear THA and give consideration to soil-structure interaction, more research is needed to confirm the appropriateness of the NZS1170.5 approach for THA in these cases.

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