STRUCTURAL AND GEOTECHNICAL REVIEW OF PIERS ON FOUNDATIONS WITH PILE INTEGRITY UNCERTAINTIES

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Abstract

Currently, an Inter Urban Train project is under construction in Mexico. Given the magnitude and importance of this work, quality control is an indispensable requirement; therefore, it is necessary to meticulously review conditions that could put at risk its structural and operational safety, as well as the entire infrastructure of the project. In this sense, a campaign of Pile Integrity Tests (PIT), was carried out to verify the condition of foundation piles. According to the results of PIT tests, provided to the authors by the company in charge of these tasks, 40 foundation piles with classification D or "doubtful" were detected, corresponding to 39 supports. Due to the possible "anomalies" of the foundation piles, detected by PIT tests, the structural and geotechnical behaviour of these supports had to be assessed by monitoring its behaviour from the structural and geotechnical points of view. To carry out the above, we performed pseudo-static and dynamic numerical analysis with elastic and inelastic mathematical models. Also, ambient field vibration studies in the supports were carried out with the aim of determining their dynamic characteristics and calibrate the mathematical models.

Keywords: urban train, condition of piles foundation, Pile Integrity Tests (PIT), columns of viaduct

1 Introduction

At the request of the Secretariat of Communications and Transport (SCT) we studied the structural and geotechnical behaviour of several supports of the Inter Urban Train (IUT) project. These supports were selected because integrity tests of the foundation piles showed different type of flaws [1]. Therefore, firstly, a campaign of Pile Integrity Testing (PIT) was carried out to verify the condition of the foundation piles. According to the results obtained, 40 foundation piles with classification D or "doubtful" were detected, corresponding to 39 supports along a specific section of the railway line. Due to these conditions, the structural and geotechnical behaviour of these supports was in doubt. Therefore, secondly, we analysed their behaviour from the structural and geotechnical points of view.
To carry out the above, pseudo-static and dynamic numerical analyses of elastic and inelastic mathematical models were performed. Previously, ambient vibration studies in some supports were carried out with the aim of determining their dynamic characteristics and calibrate the mathematical models.
To determine the structural and geotechnical behaviour of the foundation systems of the piles with doubtful integrity, the 39 supports mentioned were organised in 6 groups taking into account: the similarities of the anomaly reported and its location or depth, the location of the pile with dubious integrity in the foundation system, the stratigraphic sequence in which the foundation was built, the geometry of the support and their structural character-

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istics. The above, with the aim of reviewing the most critical supports, and based on these, validate the behaviour of different piers showing structural and geotechnical similarities. Among the supports of a section of the IUT studied, is the T3-33. In this support, the foundation pile with "doubtful" integrity corresponds to a corner pile, dubbed pile E, and the anomaly detected is a possible reduction in its diameter located at a depth of 21.3 m.
In this paper we present the experimental and numerical activities, which are part of a comprehensive study of supports with doubtful integrity, developed to assess the structural behaviour of a pier/support along Viaduct III of the IUT project.

2 Support T3-33

The T3-33 support of Viaduct III is located at kilometre 48 + 800 of the Inter Urban Train highway, in Mexico City. Figure 1 shows an elevation view of Viaduct III, and Figure 2 shows the geometry and a view of the T3-33 support.

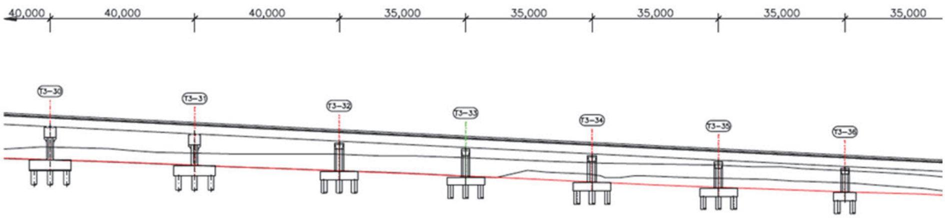


Figure 1 Elevation view of Viaduct III

3 Experimental measurement of the dynamic characteristics of support T3-33

3.1 Ambient vibration tests

An ambient vibration study was performed to determine the dynamic characteristics of the support, such as frequencies and modal shapes of vibration. These results were used to calibrate the mathematical models that will be presented in the next section of this paper. In accordance with the above, the main objectives of this study were:

- Determine the dynamic characteristics of the supports where foundation piles with "doubtful" integrity have been detected.
- Compare the vibration frequencies of supports "with and without construction flaws".
- Identify a possible pitch effect in the footing, as this effect could affect the stability of the support.
- Track the behaviour of the structure during its useful life and evaluate a likely structural deterioration due to seismic events, soil settlements, repairs, incorrect adaptations or structural modifications, etc.

This methodology is widely used for the calibration of more complex mathematical models that allow both, the design and the revision of existing structures.

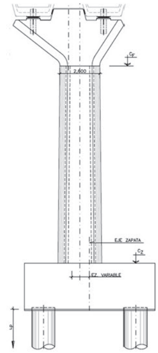


Figure 2 Support T3-33, photo and lateral view

3.2 Information processing

To provide the dynamic parameters used for the calibration of the mathematical models, time records obtained in the measurements with three triaxial accelerometers were used. The processing of the measured acceleration records was carried out by means of a spectral analysis by pairs of signals [2], calculating the spectral density, coherence, phase angle and transfer functions. The experimental methodology consists of identifying the frequencies that are associated with the maximum amplitudes observed in the spectral density functions.

3.3 Instrumentation of the T3-33 support for the ambient vibration study

Three environmental vibration tests were performed, as described below:

- For the first test, based on previous analyses and the identification of the modal shapes to be measured, three accelerometers were placed on the footing at points very close to the corners of this element. Two sensors were located in a parallel and equidistant direction from the axis of the column, while the third was located perpendicular to the other two. The above with the aim of knowing if there is any modal form associated to pitching or twisting of the footing. Accelerometers 1, 2 and 3, Figure 3.
- In the second test, to measure modes and frequencies of free vibration of the column, a sensor was placed in the free field and another on the bent. Accelerometers 4, 5 and 6, Figure. 3.
- In the third test, for the particular case of piers where the girders were already supported on them, to measure the vibrating shapes of the girders that are connected to the supports and calibrate the mathematical models, an accelerometer was placed at the centre of the span length of the girders. Accelerometers 5, 6 and 7, Figure 3.

Figure 4 shows an example of a set of frequency functions derived from the ambient vibration survey.

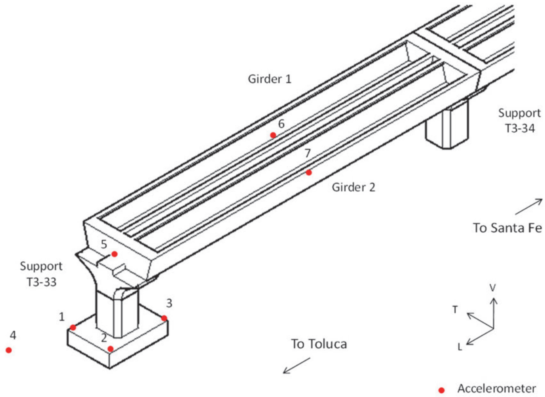


Figure 3 Location and identification of sensors

4 Modelling and structural analysis of support T3-33

Three mathematical models were elaborated: two of finite elements and one of multi-springs (see Figure 5). The latter with the capacity to represent the inelastic behaviour of the support. For the finite element models, we used “solid” elements or “frame” elements. The finite element models were prepared in the SAP2000 structural analysis program [3], and the multi-spring model was prepared using the CANNY-2010 program [4]. A dynamic step-by-step analysis was performed for each model, using as excitation a synthetic earthquake obtained from the design spectrum that was used in the original design of the project. An additional static non-linear Push-Over analysis was also performed with the multi-spring model in order to obtain the yield displacement and compare the demand (displacement design spectrum) with the load capacity of the column (capacity curve).
Prior to their analysis, all models were calibrated. The goal of this task was to match the values of frequencies and periods of vibration calculated, as close as possible to those derived from the field experimental vibration tests.

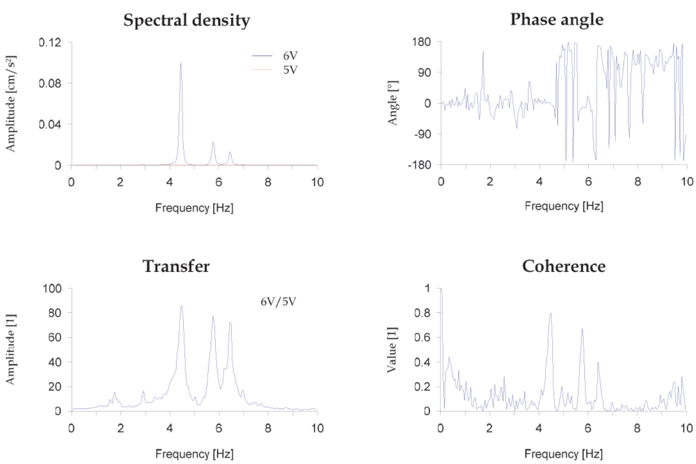
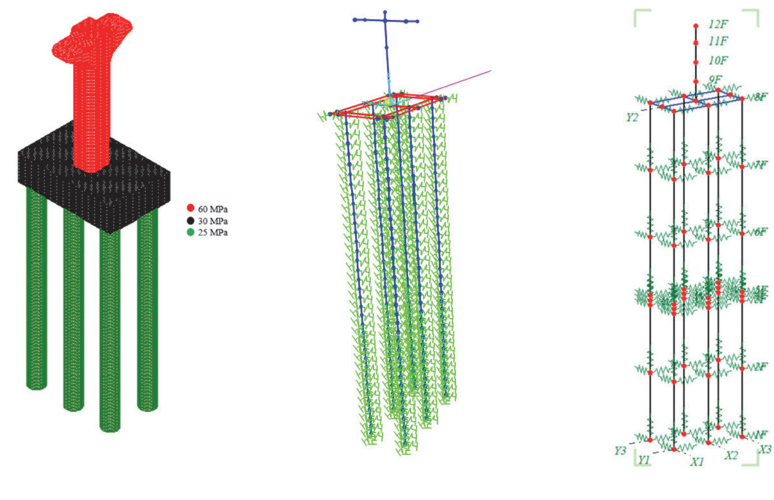


Figure 4 Frequency functions: spectral density, phase angle, transfer and coherence; points 5 and 6, component V, girder 1 of support T3-33

4.1 General modelling considerations

Once the models were calibrated, the characteristics of diameter and length of the foundation pile E with doubtful integrity, were modified obtaining seven additional models for each type of modelling. The first corresponded to the one used for the design of the project. The second was the one calibrated with the results of the environmental vibration tests. The remaining seven models corresponded to simulated conditions adverse to structural and/or dynamic performance. The models considered were as follows:

- Model 1. Materials and properties used by the designer were considered, without any reduction in the diameter of the pile with doubtful integrity (corner pile), nor variation in its length;
- Model 2. Calibrated model, without reduction of the diameter of the pile with doubtful integrity (corner pile) or variation in its length; Calibrated models 3, 4, 5, 6 and 7 with reduction in the diameter of the pile (corner pile) of 10, 15, 20, 25 and 30 %, respectively, at a depth of 21 m and a 1 m reduction in its length; Model 8. Calibrated model, without reduction of the diameter of the pile with doubtful integrity (corner pile), but reducing its length by 14 m; and Model 9, calibrated model, without the pile with dubious integrity.



a) b) c)

Figure 5 Mathematical models: a) Solid elements model; b) Frame elements model; c) Multi-spring model

4.1 Comments on the analysis of the solid finite element model of support T3-33

From the analysis of the solid finite element model, it was possible to determine that the dynamic characteristics of the support did not vary significantly for the different conditions of analysis proposed; therefore, the dynamic response would not be significantly modified by the effect of the anomaly detected in pile E. Additionally, it was observed that the stresses of pile E at 21 m depth increased due to the reduction of its effective diameter. The maximum increase in these stresses was 80 % and corresponded to the case study where the effective diameter was reduced by 30 %. It is observed that, by reducing the diameter of the pile, the tension stresses are concentrated on its perimeter, reaching values up to plus minus 29 kg/cm^2. This value is above the tensile allowable stress for a 250 kg/cm^2 concrete strength, so it would cause the section to crack.

4.2 Comments on the analysis of the frame finite element model of support T3-33

From the analysis of the structural behaviour carried out with the frame finite element model of the T3-33 support, it was determined that its dynamic characteristics did not vary significantly due to the reduction of the diameter of the cross-section of the pile or the elimination of it, coinciding with the analysis carried out with the solid finite element model. The maximum variation of the dynamic characteristics was 5 % and was presented for the case where pile E was not considered in the modelling.
Additionally, the mechanical elements of pile E, calculated at a depth of 21 m for the different analysis conditions, did not exceed the load capacity of the pile for the different effective diameters considered in the analysis.

4.3 Comments on the analysis of the multi-spring model of support T3-33

From the point of view of the dynamic response of the structural system, the reductions in the cross section of the pile at 21 m depth do not produce any change in its behaviour. The displacements at the top of the column are governed by the column and not by the foundation; therefore, the displacements without reduction in the cross section of the piles are similar to those that have reduction.
The demands due to design earthquakes do not exceed the yield displacements of the system, it remains in the elastic behaviour range.

5 Conclusions

For the analysis of the support, structural and geotechnical mathematical models of the support were carried out. The structural models were calibrated with the results of ambient vibration tests, while the geotechnical models were idealized based on information from field and laboratory exploration of the soil deposits studied. From the review of structural and geotechnical behavior it can be concluded:

- The dynamic characteristics of T3-33 support do not vary significantly for the different conditions of analysis proposed; therefore, the dynamic response of the support would not be significantly altered by the effect of the “anomaly detected” in pile E.
- The mechanical elements in pile E, calculated at a depth of 21 m for the different condition of analysis, did not exceed the load capacity of the pile for the different effective diameters considered.
- The displacements at the top of the pier are governed, by the column and not by the foundation. Therefore, the displacements of the model without reduction in pile E are similar to those of the model with reduction in the cross-section of the same pile.
- Soil-pile interaction dynamic analysis show that the T3-33 support does not present any type of problem from the geotechnical point of view.
- Soil-structure interaction effects are not important, since the level of free field maximum accelerations of the terrain and with the presence of the pier is practically the same, showing a difference of 0.01 g, and a reduction in the spectral ordinate, including the support, of approximately 0.02 g, with respect to the free field.

Thus, according to the results obtained, it can be concluded that the anomaly detected in support T3-33 will not have adverse effects on its structural and geotechnical behavior; the structural and geotechnical integrity of the support is not compromised. However, it should be clarified that these results in no way provide information related to the quality of the construction of the foundation piles.

Additionally, the same considerations can be made for supports with similar geometry, soil conditions and structural characteristics, and similar anomaly and location reported.

References

[1] Gomez, R., Escobar, J.A., Guerrero, H., Salas, M.A., Ballinas, E.: Analytical study of the railway viaduct: evaluation of the structural behaviour of supports with piles with doubtful integrity, Section III of the TIMT, group 1 (support T3-33), in Spanish, Technical Report, Institute of Engineering, UNAM, Mexico, 1997.

[2] Bendat, J.S., Piersol, A.G.: Random data: analysis and measurements procedures, 2nd edition, Wiley Interscience, New York, USA, 1989.

[3] CSI SAP2000 Version 19.2.2, Integrated Finite Element Analysis and Design of Structures, Computers and Structures Inc., Berkeley, California, USA, 2017.

[4] Kang Ning, L.: Three-dimensional nonlinear static/dynamic structural analysis computer program, Data-Input Manual, Vancouver, Canada, 2010.