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Comparison of Predicted and Measured frequencies of Monopole Structures

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Abstract

Monopole structures form a vital piece of telecommunication infrastructure in Australia. Monopoles are hollow circular tubes, typically made of reinforced concrete or steel. Monopoles are ostensibly simple cantilever structures. Crown Castle own approximately 900 of these structures across Australia. Crown Castle lease space to wireless technology operators, to encourage the sharing of physical infrastructure. It is of vital importance to Crown Castle to have the most accurate possible data on the real world dynamic behaviour of their monopole portfolio.

Often the dynamic properties of damping and first mode natural frequency are critical factors in the structural analysis of monopoles. To the authors' knowledge, there has been little dynamic testing of monopoles to date in published literature. It appears the following statement still holds true: "Specific studies on poles and monotubular towers are almost totally lacking" (Solari 1999). This paper discusses the dynamic testing of monopole structures commissioned by Crown Castle and Windtech in 2013 and 2014.

Introduction

This paper discusses a number of on-site dynamic tests of monopoles over the past 2 years. The objective of these tests was to measure the actual values for first mode natural frequencies and damping properties of monopoles. The measured frequencies were then compared with values produced in numerical models.

Due to the slender nature of monopole structures, they often have first mode natural frequencies of less than 1Hz. Therefore the first mode frequency is often a critical parameter in the analysis of monopoles, when calculating the dynamic response factor according to Section 6 of the Australian/New Zealand Standard for Structural Design Actions Part 2: Wind Actions AS/NZS1170.2. The use of 1Hz as a threshold for dynamic effects is consistent with Eurocodes and ASCE.

The testing program began in late 2013. The testing is being undertaken on an ad-hoc basis. To date, 8 Crown Castle monopoles of varying heights have been tested. This paper discusses the finding of the 4 structures tested by Windtech Consultants.

The majority of Crown Castle monopoles are concrete structures. Concrete monopoles are typically constructed by means of direct embedment of the lower part of the structure into the soil.

Spacegass Models

Simplified formulae are available for calculating the frequency of tapered poles, and the values produced are sufficiently accurate in some analyses. However, a Spacegass dynamic frequency analysis provides a more accurate picture of the first mode natural frequency.

Figure 1 shows an example of the mode shape analysis of a typical monopole using Spacegass.

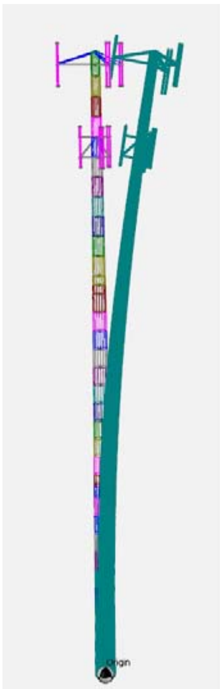

Figure 1. Screenshot of a typical dynamic mode

For the poles listed in Table 1, a detailed dynamic model of each monopole was created prior to testing. Soil-Structure interaction was not modelled, therefore each model assumed a fully fixed condition at the base of the monopole. All modal masses on the structure were modelled as accurately as possible. These masses include:

- The pole itself
- Antennas mounted on the pole
- All steel extensions above the pole
- Feeder cables mounted on or inside the pole
- Small ancillaries cable brackets, antenna mounts, etc.

A high level summary of the tested pole properties is provided in Table 1.

Monopole	Total Structure Height (m)	Material
A	30.0	Concrete
B	30.0	Concrete
C	25.0	Concrete (guyed)
D	40.0	Concrete

Table 1. Properties of the Windtech tested monopoles. Monopole D was tested 3 times.

On site measurement

The brief for each site measurement has been to measure structural damping, first mode natural frequency in 2 directions and torsional frequency.

Three accelerometers were rigidly mounted to the monopole, typically at the top head frame. The accelerometers were attached in three configurations:

- Two accelerometers were mounted in parallel and the third perpendicular to this axis.
- Two accelerometers were mounted in parallel and the third perpendicular to this axis, in the opposite configuration
- Three accelerometers were mounted at 120° separation, in line with the headframe platform

The location and orientation of the accelerometers is detailed in Figure 2:

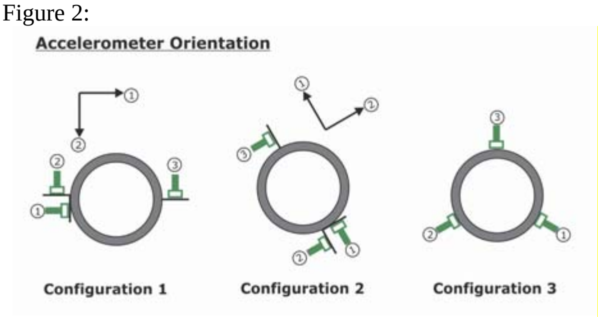

Figure 2. Accelerometer Orientation

The monopole was excited by wind actions (if present) and manually by the motions of the riggers who were located on the head frame. It is noted that the mass of the riggers themselves will marginally decrease the measured frequency of the monopole.

The output from the accelerometer was recorded using the soundbook system from SINUS Messtechnik GmbH and processed using Octave. Figure 3 shows an example of the decay response of a monopole following excitation by a rigger. Spectral analysis of the time series to determine the natural frequencies was performed using Welch's method and Figure 4 presents an example of the spectral analysis.

In the example shown in Figure 4, accelerometers were positioned in configuration 1and the monopole was excited in the direction of channel 1. The dominate motion in the direction of 1 is shown by the higher peak of channel 1 compared with 2 and 3.

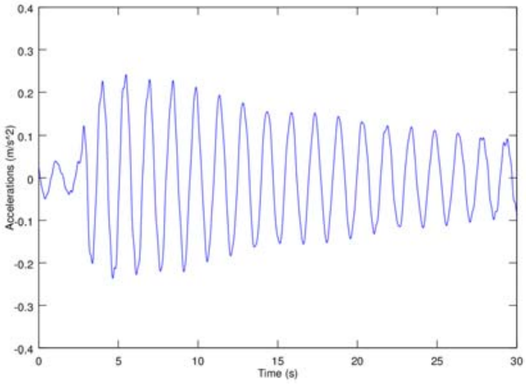

Figure 3. Time series of decay response

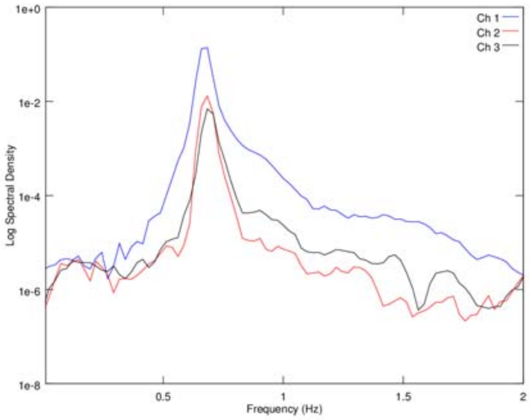

Figure 4. Spectral Analysis example

Description of Monopoles Tested

Monopoles A to C

Monopoles A and B are conventional concrete monopoles with various ancillaries located at and above 25m from the ground. No additional strengthening has been added to these monopoles.

Monopole C has been strengthened by the addition of the three tensioned guyed wires.

Monopole D

Monopole D is a 40m concrete structure in NSW. The antenna loading on this monopole has increased regularly in the past 10 years. A structural assessment of the monopole in 2014 found the structure to be overloaded and requiring a significant upgrade.

Figure 5. Monopole D prior to steel jacket installation (Test 1 Condition)

Figure 6. Monopole D after steel jacket installation (Test 3 Condition)

Crown Castle has developed a patented monopole strengthening technique, known as Steel Jacket strengthening. Steel Jacket strengthening is a method of strengthening an existing monopole in situ. A steel jacket is a large diameter steel sleeve that is installed around a monopole. There is a structural connection between the 2 structures at the top of the steel jacket. The steel jacket is designed in such a way that is stiffer than the original structure, and attracts lateral loads and bending moments away from the original structure.
Monopole D was considered a good candidate for dynamic testing, as it was earmarked for Steel Jacket strengthening. Figures 5 and 6 show the monopole before and after strengthening.

Monopole D was tested in 3 different states:

Monopole D – Test 1
The first test on monopole D was a frequency test of the unstrengthened structure. This test took place in August 2014.

Monopole D – Test 2
The second test on monopole D was a frequency test on the monopole with a 500mm concrete pad footing installed at the base of the monopole.

Monopole D – Test 3
The third test on monopole D was carried out on 31st October 2014. Test 3 was carried out after the Steel Jacket strengthening was installed.

Findings

A comparison between the results of the Spacegass analyses and the field measurements have shown that monopoles A,B,C & D have higher first mode natural frequencies than predicted by Spacegass models. The increase in frequency was calculated for each structure:

$$\Delta \text{Na} = 100 * \frac{\text{Na}_{\text{field}} - \text{Na\_sg}}{\text{Na\_sg}}$$

Table 2 presents the increases in frequencies. For monopole D the Spacegass model includes the effects of the strengthening.

Site	Δ Na
A	+1.4%
B	+5.6%
C	+21.0%
D – Test 1	+22.0%
D – Test 2	+20.0%
D – Test 3	+2.2%

Table 2. Increase in frequency from the Spacegass model to the measure site frequency.

Damping ratio values were also calculated based on the free decay of the monopole movement. Damping ratio values showed a strong consistency across all tested monopoles, and are largely in line with current code recommendations.

Discussion

There is no clear relationship between the Spacegass models and the measured frequencies for concrete monopoles. The measured frequencies for concrete monopoles have been between 1% and 22% higher than the frequency predicted in the Spacegass model.

The authors believe there are three sources of uncertainty that may account for this discrepancy:

- Concrete stiffness in real strucutures is more variable than steel stiffness and is not accurately captured in the model
- Concrete monopoles are not of the exact circular geometry modelled. In reality concrete monopoles are not manufactured symmetrically
- The concrete monopoles tested are proprietary products. The authors do not have information on the reinforcement inside the monopole, which includes prestressed tendons. It is likely that the Spacegass models significantly underestimate the material stiffness of the monopoles.

The results of frequency testing carried out by Antunes (2011) produced lower tested frequencies than predicted by their numerical models. Antunes (2011) attributed this discrepancy to an overestimation of the steel material stiffness in their numerical models. It is likely the discrepancy observed in this paper is due to an underestimation of material stiffness. Both discrepancies are due to incomplete information relating to the monopole material properties.

As per the suggestions of Silva (2006), which proposes revising effective stiffness for reinforced concrete monopoles, the input material stiffness values in the numerical model as per concrete manufacturers almost certainly need to be revised for monopoles A-D.

The testing of monopole D also confirmed that the steel jacket strengthening considerably increased the frequency of monopole D.

The stiffening effect of the steel jacket can be been modelled various ways. Our numerical model of the strengthened structure is the same as the original model, with the addition of a tubular steel section to represent the jacket. The original concrete pole and the steel jacket are connected at the top of the steel jacket as in the actual structure. The frequency measured for case 3, was a much closer estimate than the case 1 & 2. There appears to be a convergence between the measured result and the model's prediction after the steel jacket was installed. The reason for this is likely that the installed steel on site has extremely similar material stiffness properties to the modelled steel. However, the concrete monopole's material properties cannot be modelled with a high degree of accuracy. This may be confirmed through further testing on Monopoles before and after strengthening.

Conclusions

Section 6 of AS/NZS 1170.2 covers the dynamic response of structures to wind loading and highlights to designers if and when a structure is vulnerable to dynamic wind response.

Our testing suggests that frequency values for concrete monopoles tend to be underestimated by numerical models. This discrepancy appears to be due to the number of unknown variables effecting the stiffness of the concrete structure. The first mode natural frequencies predicted by numerical modelling are consistently less than those measured in the 6 tests discussed in this paper. This provides confidence that monopoles are not under designed for wind induced dynamic responses. The authors would like to emphasise that the results and the relationships described above apply only to the sample set of structures described in this paper.

Future testing will further enhance our understanding of the dynamic properties of monopoles.

Acknowledgments

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