EXPERIMENTAL MODELLING OF MULTIPLE SUPPORT EXCITATION OF LONG SPAN BRIDGES

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ABSTRACT

Eurocode 8 Pt 2 recommends that bridges longer than 400m, or bridges built on significantly varying ground types, should be assessed under the effects of multiple support excitation (MSE). However, previous analytical work has suggested that for shorter bridges MSE can also have an effect on the response. This paper outlines the results of experimental tests that confirm that for bridges as short as 200m, multiple support excitation can have a significant effect on the response of the bridge. For the bridge configurations tested, the displacements caused by multiple support excitation were up to 36% larger than when multiple support excitation was not taken into consideration. To generate the multiple input motions to each of the piers the bridge model was shaken by five parallel single axis shaking tables. The response of the bridge to three different sets of input time histories are presented in this paper. Type 1A and 1D response spectrum compatible time histories, which correspond to hard and soft soil conditions, and real data from the SMART1 array in Taiwan. The tests show that when a time delay (caused by a finite ground wave velocity) is introduced between the input motions to each pier, there is a larger response in the first and third piers, whilst there is no reduction in response of the middle pier. This occurs because the synchronous input (with all piers exactly experiencing the same input motion) only excites the symmetrical first and third modes, whilst the time-delayed input excites all of the first three modes. These typical results reveal that if we consider synchronous excitations only in the design of bridges, the response of some piers may be underestimated and hence the design may be unsafe. At present, the Eurocode 8 pt 2 does not require bridges of the length being modelled to be analyzed for MSE if the ground conditions are homogenous. However, these results reveal that even though the input motion was the same for all inputs, with only a small time delay between inputs at each pier, the response of the outer piers was significantly increased.

Keywords: Multiple Support Excitation, Bridges, Shaking Table Testing, SMART 1 Array

INTRODUCTION

The presence of spatial variations in ground motions leading to the different excitation at different support points of a structure such as the piers of a bridge is known as ‘multiple support excitation’ (MSE). Since the SMART 1 array results in 1982 (Loh et al. 1982), numerous theories have been produced which account for the effect of MSE;

1) The Wave Passage Effect (Kiuregihan & Neuenhofer 1992) – caused by the difference in the arrival times of seismic waves at different stations due to finite wave speed.
2) The Incoherence Effect (Kiuregihan & Neuenhofer 1992) – caused by the loss of coherency of the ground motion due to reflections and refractions of the seismic waves in the heterogeneous

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medium of the ground, as well as the difference in the manner of superposition of waves arriving from an extended source.

3) The Local Effect (Kiureghian & Neuenhofer 1992) – caused by the difference in the local soil conditions which can influence the amplitude and frequency content of the bedrock motion.

4) The Foundation Effect (Sextos et al. 2003) – caused when seismic motion can be modified by foundations depending on their relative flexibility with respect to the soil, as the foundation may not always be able to vibrate according to the displacement field that the incoming waves may produce.

When attempting to replicate these effects during testing physical, numerical or finite element models, complex input motions are required. However, these input motions can be combined and grouped into one of four categories (Norman et al. 2006):

a) Synchronous – whereby the inputs to all the piers of a bridge structure are the same in time and space.

b) Asynchronous – whereby the inputs to all the piers of a bridge structure are the same in space but not in time.

c) Loss of coherence – whereby the inputs to all the piers of a bridge structure are different in time and space, but are statistically dependent.

d) Incoherent – whereby the inputs to all the piers of a bridge structure are different in time and space and are statistically independent.

Theoretical and numerical analysis of MSE has consisted of the use of various numerical approaches, in particular the pseudo-static approach (Altinisik & Severn. 1981), and computer-based approaches using various 2D and 3D finite element analysis programmes (Sextos et al. 2003) to analyse structures and investigate their dynamic behaviour. Investigation into MSE for bridges has also been carried out numerically using mathematical stochastic analysis methods. These methods have included observations of the wave passage, incoherence and local site effects on long-span bridges and investigations have concluded that the wave passage effect was the most significant effect, especially in soft soils (Zhang & Lu. 2004).

Although there is a significant body of analytical work on the effects of MSE on bridges there has been little experimental work to validate the analytical models. However, previous work by Norman et al. (2004) has shown that even a simple two DOF model can be significantly affected when subjected to MSE. In this paper the effect of MSE on a more complex physical model (a 1:50 scale model of medium span viaduct bridge) is considered. In addition to the experimental work, a numerical study using a finite element (FE) model created with the Diana FE analysis package has also been carried out. The results from both the experimental and numerical models are compared and contrasted and the effect of MSE on the response of the bridge is considered.

THE PROTOTYPE VIADUCT BRIDGE

The prototype bridge is 200m long with three piers at equal spacing. The prototype dimensions were based on previous numerical MSE models which used a similar arrangement and showed that MSE can have a significant effect on the response of this size structure (Lupoi, 2005). These dimensions have also been used in other experimental work on bridges with synchronous inputs (Zapico, 2003) and Pinto (1996). The length is such that Eurocode 8 part 2 (2005) recommends considering MSE if the soil type is non-uniform but does not recommend considering MSE when the soil type is uniform.

The physical tests were performed on a specially designed MSE test bed, which comprises of a set of 5 independent single axis shaking tables, specifically designed to allow simulation of any type of MSE (Figure 1a). The model bridge can be seen mounted on the MSE experimental test bed in Figure 1b.
In the previous studies mentioned above three standard pier lengths have been considered, 21m, 14m and 7m or 420mm, 280mm and 140mm at 1:50 scale. These three different lengths will be subsequently referred to as Long, Medium and Short. There are 18 possible ways to arrange these three pier lengths, representing different ground topography; in this paper two of the extreme cases are considered, the long-long-long (LLL) (Figure 2a) and long-short-long (LSL) arrangements (Figure 2b).

**INPUT MOTIONS**

Two types of input motions were used in these tests; artificially generated time histories, which were response spectrum compatible in accordance with Eurocode 8 part 1 (2004) and real earthquake time histories taken from the SMART1 array (Loh, 1982), an array of accelerograms designed specifically to measure differences in ground motions. Two response spectra compatible displacement time histories were calculated using the method given in Clough and Penzien (1993). The Kanai/Tajimi filter was used with the recommended filter parameters for firm soil. The earthquake duration of 40 seconds real time was chosen as suitable as it significantly longer than the Eurocode 8 part 1 (2004) lower limit of 10s and provided an earthquake of reasonable duration even after scaling. The response spectra used were for a firm soil type A and a soft soil type D using a type 1 response spectra, subsequently referred to as 1A and 1D respectively. The input time history, in terms of acceleration and displacement, and the design response spectrum and actual response spectrum for the firm 1A soil type are shown in Figure 3.

For the LLL viaduct bridge two tests were run, one using synchronous inputs and the other using time delays calculated from the limits of surface ground velocity given by Eurocode 8. A surface velocity of 1000m/s was used for firm ground (1A) and 180m/s for soft ground (1D), which produces time delays of 7ms and 39ms respectively between each pier position at model scale.

The LLL viaduct bridge was also excited using real earthquake data recorded from the SMART1 array. This data was processed using the method presented in Alexander (2006). Each suite of time histories had the central accelerometer at one end, and one of the twelve accelerometers on the inner circle, with a radius of 200m, labelled I01-I12 at the other end (Figure 4). The inputs at the three intermediate points were linearly interpolated between these two end points.
For the LSL viaduct bridge the same artificially generated time histories were used as for the LLL case. However in this case the time histories were run with delays varying from 0 to 10ms in 1ms steps for the type 1A response spectra and from 0 to 50ms in 5ms steps for the type 1D response spectra.

**LLL BRIDGE LAYOUT, RESPONSE SPECTRUM COMPATIBLE TIME HISTORIES**

A typical set of pier response time histories for the LLL bridge can be seen in Figure 5 including both the numerical and experimental results for the displacements at the top of the three piers. The FE model had the same inputs as the recorded experimental inputs and was tuned so that the first natural frequency of the model matched the experimental data. The numerical and experimental results show a good level of agreement. Table 1 summarizes the results for the four tests.

For the firm soil (type 1A) with a high ground surface velocity, and therefore a short time delay, the overall response of the bridge is greater for the asynchronous case than for the synchronous case. This
is due to the fact that for the synchronous case the second mode cannot be excited as the model is symmetrical and the second mode is asymmetrical. However, when an asynchronous input occurs the second mode is excited and the combination of the first and second mode occurring concurrently leads to a greater response at piers 1 and 3. The increased response of these piers is particularly noticeable for the type 1A asynchronous excitation with pier 3 showing a 36% increase in response.

![Figure 5](image.png)

Figure 5  LLL viaduct bridge displacement at the top of the three piers when subjected to 1A time history, with a 7ms time delay between each support, (i-iii) piers 1-3 respectively.

Table 1  For LLL viaduct bridge, peak displacement at the top of each pier for each input case and both model types.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Input Type</th>
<th>Model</th>
<th>Pier 1 Peak Disp. (mm)</th>
<th>Pier 2 Peak Disp (mm)</th>
<th>Pier 3 Peak Disp (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm, 1A</td>
<td>Synchronous</td>
<td>Experimental</td>
<td>5.000</td>
<td>6.088</td>
<td>4.385</td>
</tr>
<tr>
<td></td>
<td>Numerical</td>
<td>4.217</td>
<td>6.184</td>
<td>4.310</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asynchronous</td>
<td>Experimental</td>
<td>6.284</td>
<td>6.067</td>
<td>5.945</td>
</tr>
<tr>
<td></td>
<td>Numerical</td>
<td>5.639</td>
<td>5.813</td>
<td>5.878</td>
<td></td>
</tr>
<tr>
<td>Soft, 1D</td>
<td>Synchronous</td>
<td>Experimental</td>
<td>4.639</td>
<td>6.201</td>
<td>4.443</td>
</tr>
<tr>
<td></td>
<td>Numerical</td>
<td>4.575</td>
<td>6.293</td>
<td>4.577</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asynchronous</td>
<td>Experimental</td>
<td>1.837</td>
<td>1.770</td>
<td>2.075</td>
</tr>
<tr>
<td></td>
<td>Numerical</td>
<td>1.849</td>
<td>2.485</td>
<td>2.128</td>
<td></td>
</tr>
</tbody>
</table>

However, for the soft soil (type 1D) with a low ground surface velocity, and therefore a long time delay, the overall response and peak response of the bridge are significantly reduced in the asynchronous case. This is due to the fact that the time delay is large and therefore the inputs are effectively out of phase, so the first mode is not excited.

We can see from the results that the overall peak displacement, for this bridge arrangement, occurs with soil type 1D under synchronous excitation. This is not surprising as this response spectra includes a significantly larger input acceleration. However, whilst the firm soil shows an increase in the response for the asynchronous case, the soft soil case shows a substantial reduction in the response for the asynchronous case. This is partially due to the increased time delay and also due to the fact that different time histories generated from the same response spectrum can produce different responses when the inputs are asynchronous.
Figure 6 and Figure 7 show partial snapshots of the deck’s displaced shape in plan, taken from the numerical model. In Figure 6 (synchronous excitation) the response of the bridge is completely symmetrical, whereas in Figure 7 (asynchronous excitation) we can see that a large part of the response is non-symmetrical. This supports the argument that synchronous excitations cannot excite asymmetrical modes but when asynchronous excitations occur, both symmetrical and asymmetrical modes are excited and the combination of these modes can lead to an increase in response.

![Figure 6](image-url)  
**Figure 6** The displaced shape of the LLL viaduct bridge deck calculated using FE analysis at discrete time intervals of 0.1s for the 1A time history, synchronous input.

![Figure 7](image-url)  
**Figure 7** The displaced shape of the LLL viaduct bridge deck calculated using FE analysis at discrete time intervals of 0.1s for the 1A time history, with 7ms delay between supports.

**LSL BRIDGE LAYOUT, RESPONSE SPECTRUM COMPATIBLE TIME HISTORIES**

The LSL viaduct bridge represents a bridge spanning over a double valley. In this configuration the bridge is again symmetrical and the first mode is a symmetrical mode, however the second mode frequency is much closer to the first mode than in the LLL case. The same artificially generated time histories were used as in the LLL case. Each test was repeated twice and both sets of results were included in the analysis. The FE analysis model again had the same inputs as the recorded experimental inputs and the FE analysis was run with both sets of inputs.

**Response Spectra Type 1A Inputs:** Figure 8 shows the peak responses and the subspace gradients (Norman et al. 2005) for all 22 tests performed. The peak response shows that the experimental results varied when repeated whilst for the numerical model the two values fall much more closely together. As the inputs into the numerical model were those measured during each experiment we can see that the experimental model was much more sensitive to very slight changes in the input motion and that other factors such as non-linear damping must be altering the response of the experimental model. However the difference recorded for the numerical model is much smaller and we can be certain that the only change, in this case, was the input motion.

Generally the peak response plots show a good correlation in peak response between the experimental and numerical models. For piers 1 and 3 the experimental and numerical peak displacements increase as the delay increases. For the middle pier (pier 2) the numerical values show a slight increase with increased delay while the experimental values increase initially but then reduce.

The subspace plot gradient is a single number indicator on the agreement between the experiment and the analysis. If the gradient is greater than 1 the numerical method is overestimating the total response, if it is less than 1 it is underestimating it. Whilst the peak response only gives an indication of how well the models compare at a single data point, the subspace plot gives an indication of how well the data agrees for the time range it is considered for. In this case two ranges are used, 0.5s-1.5s and 0.5s-2.5s. In both cases the start point is 0.5s because before this time no significant excitation occurs,
durations of 1s and 2s are chosen because these capture the time when the response is at its greatest and the input reaches its peak.

Figure 8  Peak response (a) and subspace gradient (b) for piers 1-3, (i-iii) respectively of the LSL viaduct bridge comparing the experimental and numerical model excited by 1A time history with varying delay.

From Figure 8 we can see that the subspace plot gradients are generally close to the ideal value of one. For pier 1 the values are always less than one but as the time range increases the value increases suggesting that the initial response is underestimated, whilst the later part of the responses matched much more closely. No significant change in gradient occurs at this pier as the delay is increased. For the middle pier the two lines show a very similar trend, the numerical values producing a larger response for small or no delays, but as the delay increases so the gradient reduces to below 1. In this case this trend is also reflected in the peak response data. Finally for pier 3 the smaller time range produces a larger gradient than for the greater time range. For the smaller time range the gradient rises to a peak at 5ms, and then falls as the delay increases. For the larger time range the gradient again rises but at a lesser rate with a peak at 6ms and it converges with the other line at 10ms.

Response Spectra Type 1D Inputs: For the response spectra type 1D a greater range of time delays was used as the surface wave velocity given in Eurocode 8 part 2 (2005) is significantly less than for ground type A. As for the 1A spectra a total of 22 tests were run, two with each input set with varying delays. The peak response and subspace gradients were again used to compare the experimental and
numerical results. In this case however, except for pier 3, the peak response reduced as the time delay increased.

LLL BRIDGE LAYOUT, SMART-1 ARRAY TIME HISTORIES

As well as using artificially generated time histories, real time histories recorded from the SMART-1 array have been used to simulate MSE on the LLL bridge arrangement. In this case the inputs model a loss of coherence but they are statistically related. In this set of experiments, each group of inputs was run four times and then compared. It was decided not to run a synchronous case because it was not clear what is the right case for comparison. If the case which produces the worse effect was used then it is likely no MSE case will exceed it, likewise if the case with the least effect was used then MSE will almost certainly produce larger effects. Therefore depending on what we are trying to demonstrate we would be able to pick an appropriate synchronous case. Instead the results are compared against each other showing the trend in response as the bridge is moved around the SMART-1 array.

Figure 9  Peak response (a) and subspace gradient (b) for piers 1-3, (i-iii) respectively of the viaduct bridge comparing the experimental and numerical model excited by displacements calculated from the SMART-1 array using the stations I01-I12.

Figure 9 presents the peak displacement response and subspace gradients for the comparison between numerical and experimental data. The graphs are presented in the same fashion as for the artificially generated time histories, but in this case the x-axis, rather than showing delays, shows the station at one end of the bridge. The other end of the bridge is always located at the central station of the array,
station C00 (Figure 4). The twelve stations are set out at equal radius, with 30 degrees between each one, thereby forming a full circle. A clear trend can be observed in the peak response where the values start low at station I01, increase to a maximum at station I04, then reduce to a minimum at station I06 for piers 1 and 2 and I07 for pier 3. They then increase again to a maximum at station I10, 180 degrees round from I04, before reducing to a minimum at station I12. This trend shows the importance of orientation on the response of the bridge, however this is not necessarily an effect of MSE. The increase in response of all three piers is comparable, but the percentage increase for piers 1 and 3 is significantly larger (up to 110%). Therefore, whilst pier 2 shows the greatest overall response, as the bridge is governed by the first mode, the greater increase in responses for piers 1 and 3 suggest that the second mode is also affecting the bridge’s response.

The correlation between the two models, experimental and numerical, is much better than for the artificially generated time histories, with both values matching much more closely. It is worth noting that the variations in peak response are also much more marked. The subspace gradient plots again show a high level of agreement, with the gradient being closer to one when the peak response is larger and also when only a range of 1s is considered. In this set of data there is a substantial reduction in the subspace gradient when the range is increased to 2s, but the trend in gradient remains the same. This reduction in gradient occurs because the time histories are shorter and have more energy occurring at the start of the earthquake, the response typically reaching a peak early on and then reducing rapidly.

![Graph](image1)

**Figure 10** The displacement response of the LLL viaduct bridge experimentally and numerically using station I04 to calculate the displacement input, (i-iii) piers 1-3 respectively.

![Graph](image2)

**Figure 11** The displaced shape of the LLL bridge deck calculated using FE analysis at discrete time intervals of 0.1s for the Smart 1 input data using station I04.

Figure 10 shows the response of the three piers for case I04, one of the maximum response cases. All three experimental and numerical time histories show a strong level of agreement, although the numerical response dies out more quickly in the second half of the time history. Looking at Figure 11 we can see that the response is significantly dominated by the first mode, however the response is not completely symmetrical, and the second mode also contributes to the response of piers 1 and 3.
CONCLUSIONS

In these tests the experimental and relatively simple FE model showed a high level of agreement. The agreement was greatest when the response was large and when the damping did not play a significant part in the response. The response of the middle pier generally showed greater agreement, especially in the LLL model, where the numerical model was tuned to the first mode of the physical model. However in the LSL model, where the tuning was a more significant process and both the first and second mode were tuned, the response of piers 1 and 2 showed good agreement and the response of pier 3 showed better agreement as the delay was increased.

These tests have shown that whilst the asynchronous 1A time histories produced larger results for both bridge arrangements, the 1D time histories did not. At present these and other tests do not suggest that the difference in response, when considering asynchronous inputs, is specifically related to the different response spectra but rather that the behaviour of the bridge is related to the specific form of the time history. We can nevertheless conclude that asynchronous inputs, even with small time delays sometimes produce increases in response, but that they can also significantly damp out the response of a bridge and which occurs is dependent on the original time history.

Finally, from the SMART-1 array data, we can see that orientation has a significant effect on the response of the bridge, and that MSE effects can excite the asymmetrical modes producing larger responses in piers 1 and 3, without reducing the response of the central pier.

REFERENCES


