The effect of foundation rocking on structural response

Robert Mattholie and Alastair Pickard write about their joint undergraduate project at University of Bristol which was commended in the Model Analysis Award 2003

A common assumption in earthquake analysis is that the foundation of a structure is fixed rigidly to the ground, and that there is no uplift under earthquake excitation. This investigation, carried out as a 3rd Year Undergraduate Research Project in the Department of Civil Engineering at the University of Bristol, aimed to qualitatively examine such an effect on the structural response of a model.

Current design codes adopt a specific level of internal structural damping. The primary conclusion of this investigation is that foundation uplift introduces a significant external damping mechanism. This increases overall system damping leading to a marked reduction in structural deformation.

The physical model

The physical model was kept simple by limiting it to a single storey. Flat spring steel columns inhibited out-of-plane displacements, and pins in the base of the structure located into the base plate allowed uplift whilst preventing the model from sliding. Fig 1 shows a schematic of the model, and Fig 2 is a photo of the model in action on the shaking table.

The angle of base separation shown in the schematic is greatly exaggerated for clarity. The observed uplift phenomenon actually caused very small angles of base separation allowing vertical displacements to be neglected.

It was relatively straightforward to examine the total displacement of the structure using accelerometers attached to the model. However, crucial to the investigations was the relative deformation between the internal structural deformation (i.e. column deformation) and the overall structural displacement. This was measured by recording the induced flexural strain occurring in the columns during testing.

The frequency response function

The experimental work conducted focused upon the assessment of peak responses around the natural frequency of the model. The frequency response function (FRF), a type of transfer function that provides a graphical approach to the analysis of systems, affords a useful qualitative measure of a particular structural response for a given energy level of excitation over a range of frequencies. Transfer functions are frequently used in engineering to characterise the input-output relationships of linear time-invariant systems.

A transfer function is defined to be the ratio of the Laplace Transform of the system output (response function) to the Laplace Transform of the system input (forcing function). Consider a system with a forcing function u(t) and a response function x(t); the Laplace Transforms of these input and output functions are given by U(s) and X(s) respectively. Thus, the system transfer function G(s) is defined to be:

$$G(s) = X(s) / U(s)$$

where X(s) and U(s) are polynomials of s, a complex variable

Essentially, the FRF provides a ratio of the peak system output (model response) to the peak system input (exciting energy of the table) over a range of frequencies. Peaks in the FRF are associated with resonance, with the width of the peak being proportional to the damping.

Experimental procedures

System input for the FRF was provided by an accelerometer on the shaking table and system output by a strain gauge attached to one of the model's columns at a point of maximum flexural strain. At increasing levels of base excitation, the peak FRF amplitude could then be plotted against a corresponding RMS table acceleration.

The FRF characteristics were further analysed to obtain an estimate for system damping. This value of damping was recorded and plotted similarly against the corresponding RMS table acceleration.

Experiments were carried out for both the fixed and free base cases.

Results and analysis

Fig 3 shows a plot of the key data from the experiments. It shows clearly the contrast between the fixed and free base cases in terms of FRF peak amplitude and damping.

In the fixed base experiments, FRF peak amplitudes remained approximately constant over the range of excitation levels. The FRF provides a ratio of output to input functions, so the constant FRF values represent a linear relationship between relative deformation of the model and base excitation. This effect is also observed in the consistent values of system damping recorded over the range of excitations.

The data sets for the free base experiments have a clear change in trend at the same RMS value. The drop in FRF peak amplitude and the rise in system damping both occur at a level of excitation where the effects of uplift first become noticeable. This dramatic increase in system damping, approximately by a factor 5 over the range of excitation levels, is the fundamental

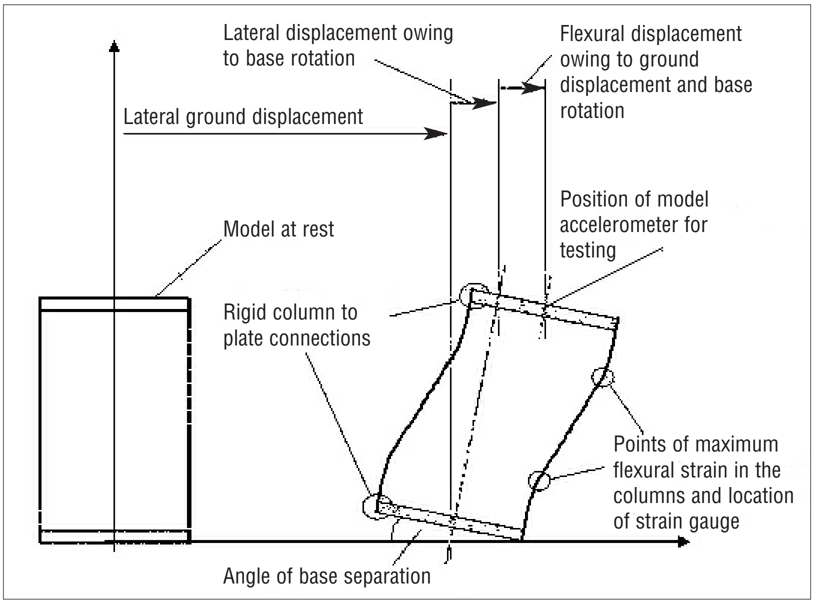

Fig 1. A schematic of the model

finding of this investigation.

Damping is the determining factor in the response of any structure subjected to dynamic loading. The damping ratio of a structure, ξ, is defined as the ratio of system damping to critical system damping (the damping level required to return a deformed structure to its original state after just one oscillation). The deformation response factor, R_D, is defined as the ratio of maximum dynamic displacement to maximum static displacement, and provides a measure of the severity of a system's dynamic response. It can be proved that peak R_D at a system's natural frequency is given by 1/2ξ, so a factor 'n' increase in system damping would lead to a factor '2n' decrease in the peak R_D value.

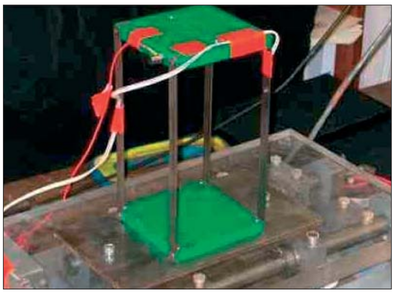

Fig 2. The model in action on the shaking table

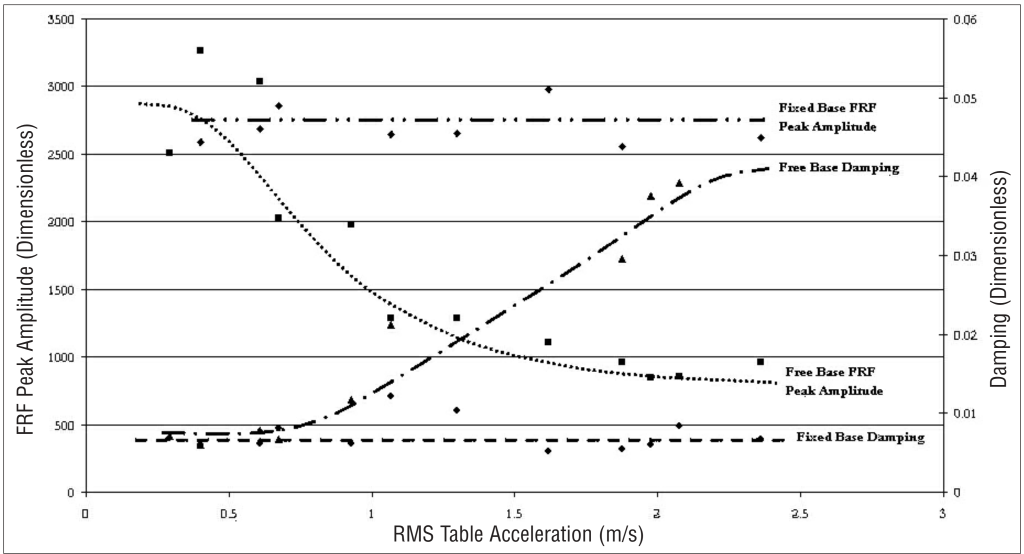

Fig 3. RMS Table Acceleration vs FRF Amplitude & Damping

Therefore, in this experiment, a factor 5 increase in system damping should correspond to a factor 10 decrease in the peak deformation response factor.

Conclusion

The uplift phenomenon provides external damping and causes a significant increase in the total damping of the system. This increase in total system damping causes a dramatic reduction in internal structural deformation.

Evidence of structures exceeding their expected capabilities under earthquake loading could possibly be attributed to this phenomenon. It is important to note that base uplift is likely to be occurring in most slab foundations when subjected to dynamic loading.

Inevitably this investigation has its limitations, not least the small amount of data recorded. However, with further experimental and analytical research its implications could be incorporated into future structural design.

A full report on this project is available in the Institution library. se

• The Model Analysis Award is an annual competition for experimental projects carried out by final year undergraduates and first year postgraduates. The competition is organised by the Institution's Study Group on Model Analysis as a Design Tool and is launched in March each year.