Shaking Table Substructuring for Soil Structure Interaction

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• Summary
The seismic response of a soil-foundation-structure system is governed by the interplay between the dynamics of the soil, the structure and the earthquake.

Analytical and numerical techniques have been and are being developed to aid with safe design of SSI systems.

Physical modelling is required to validate proposed design tools.
Experimental investigation of SSI

Option 1 - Site tests

- Real soil profiles
- Large scale testing
- No control of ground motion
- Used to estimate how SSI affects damping and natural frequencies

Site test (Shouping, 2004)
Option 2 - Laboratory tests

- The soil-structure system is the test specimen
- Specialist apparatus required – shaking table, centrifuge, soil container.
- Modelling is at small scales due to the size/capacity limitations of test apparatus
Option 3 – Real time dynamic substructuring RTDS

- The test structure is split into two linked parts
- The unpredictable component is tested in the lab
- The remainder is modelled numerically
- Interface force is measured
- Commensurate motion applied by a transfer system
Shaking table RTDS control

- Historically, RTDS has used standalone actuators
- SSI RTDS demands the use of a shaking table
Generalised RTDS control loop

$d$ – reference excitation
$y_N$ – desired displacement
$u$ – command signal
$y_P$ – achieved displacement
$f$ – feedback force

Challenge 1 – to obtain a realistic desired displacement.
Challenge 2 – to achieve stable and accurate RTDS by nullifying transfer system dynamics using a controller.
Time-delay model

- Most prevalent control scheme is delay compensation

\[ y_P(t) = u(t - \tau) \]

\[ \Rightarrow G_{ts} = \frac{y_P(s)}{u(s)} = e^{-\tau \omega i} \]

- Assumptions inherent in the time delay model:
  (i) Constant magnitude, i.e. \( |G_{ts}(s)| = 1 \)
  (ii) Phase proportional to frequency, i.e. \( \angle G_{ts}(s) = \omega \tau \)
Transfer system dynamics

Standalone actuator  Shaking table
The effect of transfer system dynamics on RTDS stability

- Dynamic stability of closed loop feedback systems analysed using the root locus technique.
- Physical to numerical mass ratio is taken to be the variable parameter of interest.
- Stability predictions are reliable only once comprehensive transfer system dynamics are taken into account.
The effect of transfer system dynamics on RTDS accuracy

Control schemes that do not account for comprehensive transfer system dynamics such as delay compensation have a narrow viable bandwidth curtailed at low frequencies.
Full State Compensation via Simulation (FSCS)

A conjunction of Inverse Dynamic Compensation via Simulation (Tagawa, 1994) and full state feedback configured to provide a 4\textsuperscript{th} order accurate inverse dynamics command signal free of noise.
Full State Compensation via Simulation (FSCS)

Error feedback (via the $k_e$ parameter) can be used to compensate for discrepancies between the dynamics of the real and virtual shaking tables.
FSCS Accuracy

- Transfer function relatively flat
- Small delay remains (2-3ms)
- Feedback ($k_e$) enhances low frequency performance
FSCS Stability

- Compared to the no controller (‘NC’) and delay compensated (‘DC’) cases, FSCS generally enhances stability.
- Exception is when structures are very lightly damped.

Here: $k_e = 0$, $\omega = \omega_N = \omega_P$,

$$\xi = \xi_N = \xi_P, \quad \sigma = m_P/(m_P+m_N)$$
Benchmark SSI test

- Structure
- Soil
- Soil Container
- Shaking table
Shaking table
Shear stack soil container

- Filled with dry sand (Hostun S28) and excited in the long-direction
- Restraining frame restricts $x$ and $z$ vibrations
- Rough end walls & base, lubricated side walls
- Composite stiffness of box significantly less than that of deposit – the deposit drives the response
Test configuration

• 1DoF super structure
• Scale factor 30
• Plane strain

Benchmark test
Frequency response of the benchmark test system

Sand deposit – 29Hz

Fixed base oscillator – 23Hz

SSI system – 11Hz
RTDS implementation

Fixed-base parameters:
• $m_p = 50$ kg
• $\omega_p = 23$ Hz
• $\xi_p = 5\%$

Modelling SSI frequency response:
• $m_N = 120$ kg
• $\omega_N = 16$ Hz
• $\xi_N = 14\%$
Vrancea (1977)

Friuli (1976)

Response acceleration time history

Response acceleration power spectra
Excitation magnitude

1x

2x

RTDS Benchmark
• Agreement between RTDS and benchmark test is good up to 5Hz and reasonable up to 10Hz
• Rocking mode becomes dominant after 10Hz
• Multi-axis RTDS required to model SSI phenomena comprehensively

• Agreement worsens as amplitude of excitation increases and the response of the linear soil model diverges from the nonlinear sand deposit
• More realistic soil model required
Summary

• With ‘complex’ transfer systems, application of the time delay model can result in poor RTDS performance.
• RTDS stability predictions become reliable once comprehensive transfer system dynamics are accounted for.
• A new controller, Full State Compensation via Simulation (FSCS), offers an enhanced RTDS performance compared to delay compensation.
Summary

• Uni-axial RTDS cannot simulate the phenomena associated with SSI. Multi-axis RTDS is required for SSI systems exhibiting rocking/uplift.

• Linear lumped-parameter soil-foundation models limit the scope of RTDS tests. Alternatively, SSI nonlinearities (elastoplastic soil response, foundation rocking/sliding/uplift) can be incorporated within the RTDS algorithm using numerical models of increased sophistication.