FoRCy: Rocking Shallow Foundation Performance in Slow Cyclic and Monotonic Experiments

Abstract

In recent years, numerous centrifuge (e.g., Rosebrook 2001; Ugalde et al. 2007; Gajan and Kutter 2008; Deng et al. 2012; Hakhamaneshi et al. 2012; Liu et al. 2013; Allmond and Kutter 2014; Loli et al. 2014) and 1*g* shake-table (e.g., Shirato et al. 2008; Drosos et al. 2012; Antonellis et al. 2015; Tsatsis and Anastasopoulos 2015) experiments have been performed, demonstrating that rocking shallow foundations can be designed to provide re-centering and energy dissipation with little damage. Each test series studies specific response aspects by varying soil profiles, structural properties and ground motions, while still contributing to the larger goal of understanding and predicting rocking shallow foundation performance during dynamic shaking. As a result of this cumulative body of research, the concept of a controlled share of ductility demand between the superstructure and the foundation as a key ingredient for a rationale and integrated approach to the seismic design of foundations and structures has been gaining acceptance within the research and practicing earthquake engineering community (e.g., Mergos and Kawashima 2005; Kutter et al. 2006; Anastasopoulos et al. 2010; Pecker et al. 2013; Kutter et al. 2016).

This database (*FoRCy*) contains data from a large subset of slow cyclic and monotonic experiments, whereas, a separate database compiles data from dynamic shaking tests (*FoRDy*). Currently, the FoRCy database compiles data of shear-wall type structures founded on rocking shallow foundations from **seven centrifuge and three 1*g* shake-table tests, with thirteen different soil profiles, nearly seventy slow cyclic tests and ten monotonic tests, over ten different loading protocols, totaling 455 event model case histories**.

CONCEPT OF ROCKING FOUNDATIONS

Figure 1 shows a simplified soil-footing-column system. This system is subjected to the vertical load *(P)* applied to the center of gravity of the structure, and the inertial lateral load *(V)* applied at a height (*H)* above the base of the footing. The footing has a length of *L* (parallel to the shaking direction), width of B (normal to the shaking direction), and area of $A = B \cdot L$. These loads can cause the base centroid of the footing (point O in Figure 2) to rotate *(θ)*, slide horizontally *(u)* and settle *(s)*. For non-rigid soil, as the footing rocks, it does not bear on a sharp corner of the footing. Instead, a minimum contact area (A_c) is required to support the vertical load. The moving of the contact area results in a curve interface, with localized bearing failure apparent near the edges of the footing (Wiessing 1979). For rectangular footings, loaded along the length of the footing, the critical contact length, L_c, is directly related to the critical contact area as $L_c = A_c/B$. The value of A_c represents the minimum area of the footing required to support the vertical load when the soil's bearing capacity is fully mobilized on the contact area. The "critical contact area ratio" is used to denote the ratio of A_c to the total plan area of the footing.

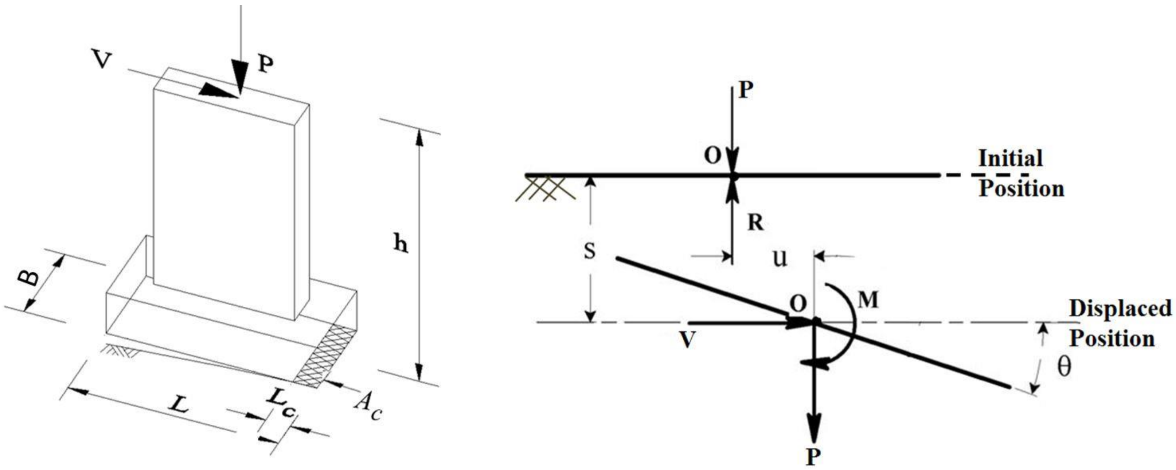

Figure 1. Rocking foundation deformation parameters (Gajan and Kutter 2009, Deng and Kutter 2012).

DATABASE OBJECTIVES

As noted in Allmond and Kutter (2015), combining datasets from different experiments into a single database can as a beneficial tool to the community through the following features:

- **Comprehensive Database**: The database includes data produced at different experimental scales (centrifuge, large and small-scale 1*g* tests), at different research facilities and by different research teams, spanning a variety of soil profiles, structural and rocking system properties, and loading protocols, for a total of 462 event case histories of slow cyclic/monotonic foundation rocking.
- **Data Consistency**: The database helps validate findings of individual tests through comparison of similar test cases, and can enhance understanding by analyzing a larger dataset as a whole instead of looking inward at individual experiments.
- **Ease of Use**: The database allows users to easily browse through many tests at once and compare the important features of each test. Furthermore, the centralized storage, and the detailed and consistent style of data archiving provides researchers and practitioners with easy access to ready-to-use data without the need to contact the authors of each test series.
- **Expansion Potential**: The database allows researchers to easily add experimental data to the existing *DataStore*, to further validate and expand knowledge of rocking shallow foundation performance under seismic excitation. Intentionally, the current version of the database is not an exhaustive compilation of all up-to-date relevant experimental studies, but it is hoped to set the ground for other researchers to add their data from existing and future experiments.

DATABASE OVERVIEW

Database Organization

The data are organized and presented as a spreadsheet. The database consists of rows (for each station) and columns (different station identifiers). Each station represents the response of a test model to either a single packet (typically series of cycles of similar amplitude) or a series of packets. If a model container includes a sequence of 8 packets of different amplitudes, that experiment produces a total of 8 station-events.

The columns of the database provide the supplemental information for each station-event and are categorized by Project and Test Series, Facility & Equipment, Packet, Scaling Quantities, Soil Layer(s) Properties, Footing Properties, Superstructural Properties, Bearing Area Properties, System Properties, Input Loading Protocol Properties, Key Plots and Time History Data, Summary Performance Results, and Miscellaneous. A separate document **(*FoRCy Column Definitions*)** defines individual columns of the database. Each column is also categorized by the entered data format as either *Text*, *Integer*, *Floating*, *Date*, *File(s)* or *URL*. Each rows (in FoRCy Column Definitions) is categorized and color shaded by data type as follows:

- **Informational (grey)** - a broad category of any supplemental information which was not directly measured or calculated (e.g. test name, soil material type, structure name).
- **Measured (green)** - values which were directly measured in the lab or during testing without manipulation (e.g. soil layer thickness, footing width).
- **Derived (orange)** - calculated using a known expression or equation to manipulate measured data (e.g. foundation bearing pressure).
- **Inferred (red)** - data that required engineering judgment with known properties during testing, or was derived using several methods (e.g. relative density, bearing capacity).

Test data can be browsed, sorted and compared online using the available *NEEShub* tools, or downloaded as a single spreadsheet in *.csv* format, whereas individual files (e.g., *Structural Image*, *Time History Data*) can only be accessed, viewed and downloaded individually.

Table 1. below indicates the location of each soil-structure model in the database and provides a summary description of the testing series, soil profile and footing shape properties.

Test Series	Test Type	Row Number	No. Monotonic Tests	No. Cyclic Tests	Footing Shape	Soil
MAHS-1	Centrifuge	2-89	0	16	Rect. & H	Nevada Sand
LJD01	Centrifuge	90-105	0	4	Rect.	Nevada Sand
P2011SQF	Small-Scale 1g	106-292	9	19	Square	Longstone Sand
MAH03	Centrifuge	293-306	0	2	Rect.	Nevada Sand
MAH01	Centrifuge	307-330	0	4	Square	Yolo Loam
Model-H	Small-Scale 1g	331-351	1	2	Square	Toyoura Sand
Model-L	Small-Scale 1g	352-386	2	4	Square	Toyoura Sand
SSG-02	Centrifuge	387-409	0	5	Rect.	Nevada Sand
SSG-03	Centrifuge	410-427	0	4	Rect.	Nevada Sand
SSG-04	Centrifuge	428-436	0	3	Rect.	Nevada Sand
TRISEE-HD	Large-Scale 1g	437-451	0	3	Square	Ticino Sand
TRISEE-LD	Large-Scale 1g	452-463	0	3	Square	Ticino Sand

Use of Abbreviations

When appropriate, the abbreviations *n/a* (not applicable), *n/m* (not measured), and *n/r* (not reported) are used as follows:

- **Not applicable (n/a)**: When a column inquiry is not applicable to a specific event (e.g., the undrained shear strength for a sand layer).
- **Not measured (n/m)**: When a column inquiry was either not measured in the test, or while measured was taken, it has been concluded that it is poor and should be neglected.
- **Not reported (n/r)**: When a column inquiry is chosen to not be reported yet for reasons such as: sufficient good quality data have been collected but further post-processing is needed; inconclusive at current stage if measurement is reliable.

It is noted that when the data format of a column is numeric, *n/a*, *n/m* and *n/r* are replaced by *7777*, *8888* and *9999*, respectively, to allow for sorting and comparing the data in the *DataView*, and easier post-processing of the data files containing the time histories of key response parameters.

Co-ordinate System and Sign Convention

The database uses a common right-handed co-ordinate system to report sign-dependent quantities, displacements, and forces. In this co-ordinate system, x-axis is parallel to the horizontal ground excitation and positive z-axis extends vertically upwards, as shown in ***Figure 2***. Exceptions to this co-ordinate system are made in the z-direction. Settlement is defined positive as the downward movement of the footing (*s*), whereas axial load is defined positive as the compressive vertical load at the soil-footing interface.

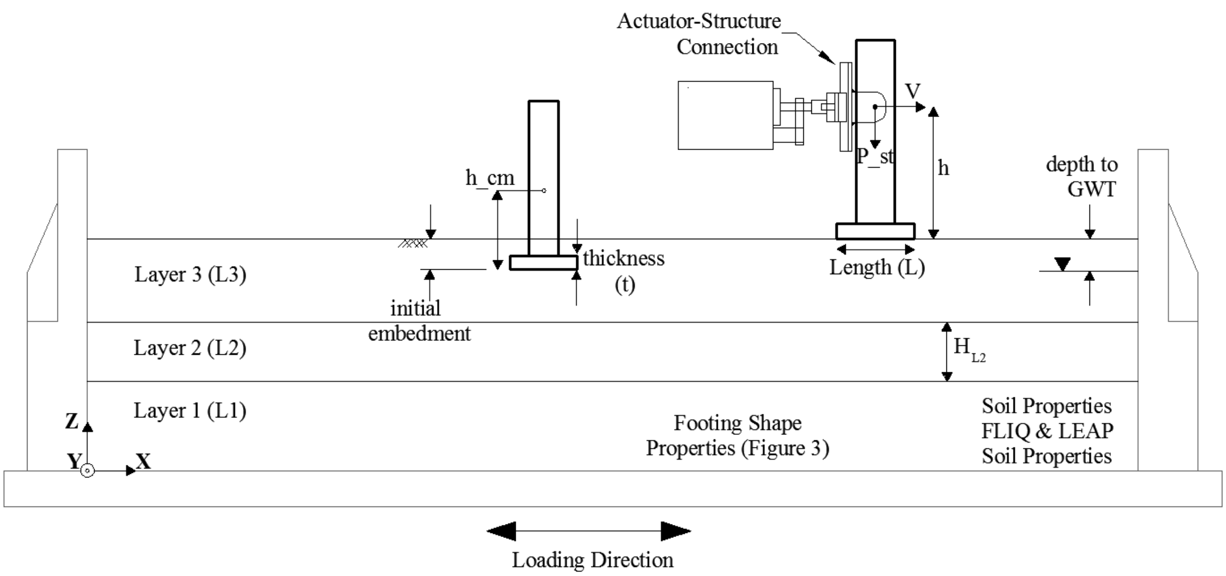

Figure 2. Elevation view of model container in a hypothetical test to define nomenclature used to describe data included in the database of rocking foundations during slow-cyclic and monotonic loads (not to scale).

Soil Profile Properties

Critical soil layer properties (e.g., layer thickness, relative density or undrained shear strength, total density, and water content) are summarized in the *Soil Profile Properties* columns of the database. Those interested in the index properties of the soil materials used to construct each layer are referred to the data report and other references relevant to each test series. Index properties for soils used in other experiments at the Center of Geotechnical Modeling (University of California at Davis) can be found at ***FLIQ Soil Properties*** (Allmond et al. 2014) and ***LEAP Soil Properties*** (Carey et al. 2015). Please note that index properties of Nevada sand, in particular, were observed to vary depending on the delivery date (e.g., e_{max} and e_{min} used for relative density) as noted by Carey et al. (2015).

Structure Properties

Footing Shape Parameters

The database includes parameters to describe the shape of footings that are non-rectangular and non-circular, as well as footings with their primary axes rotated with respect to the horizontal ground excitation axes (**Figure 3**). A rectangular footing is described by its length (L) and width (B), that are the footing side dimensions parallel to the x-axis and y-axis, respectively. If the footing is skewed, *Skew_Angle* is defined as the footing rotation about a downwards vertical axis that is required to align L_f and B_f with the x and y axes. For non-rectangular and non-circular footings, the parameter $MAR = A_{missing} / A_{rect}$, called the *Missing Area Ratio*, is introduced to describe the footing shape. In addition, t_{f_web} and t_{f_flange} are used for H-shaped or C-shaped footings to describe the thickness of the footing flange and web, respectively, whereas B_{f_min} is used for trapezoidal footings as the minimum footing width value.

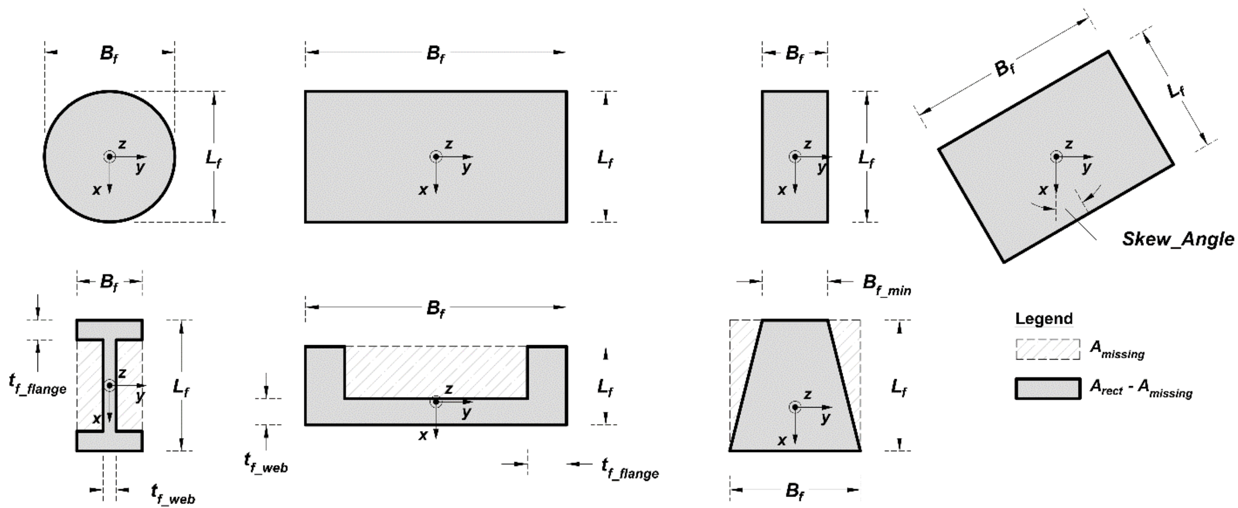

Figure 3. Schematic illustration of footing shape parameters used in the database (Hakhamaneshi and Kutter 2016).

Summary Performance Results

Summary performance results provide critical response measures of the rocking system in the xz-plane. **Deformation demands** include the peak, incremental peak, residual and incremental residual values for structural rotation, footing rotation and footing sliding, as well as the residual and incremental residual values for footing total settlement. An example calculation of the above values for a hypothetical footing rotation time series across two sequential cycles is given in ***Figure 4***. In addition, cumulative footing rotation demand, conceptually the sum of all the local peaks of the rotation series that exceed an arbitrary threshold rotation, is also reported following the approach described in Deng et al. (2012).

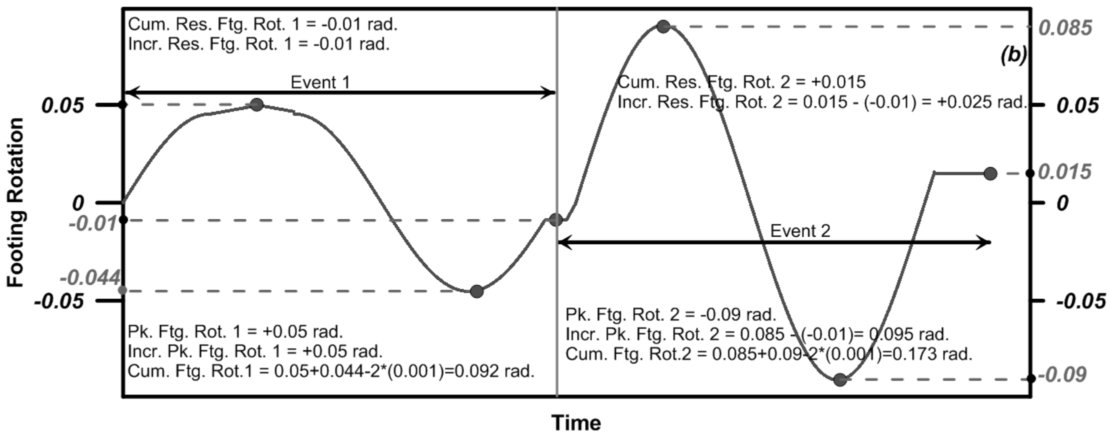

Figure 4. Illustration of the method to obtain the cumulative, peak and residual footing rotation.

DATA CURATION

All of the data uploaded to the database on August 2016 has been checked, primarily by the first author, to make sure that are consistent and reasonable. Some of the most important specific checks are listed below.

1. Ensuring that data table entries that are independent of the time series data are consistent with relevant references and with each other. For example, check that footing bearing pressure uses the reported footing axial load and footing plan dimensions.
    a. Confirm that time series data follow the sign conventions, are sensible and consistent with each other and with other references. Plot the moment versus rotation, settlement versus rotation, shear load versus sliding and settlement versus sliding and confirm that are consistent with relevant references and reasonable. Shear load-sliding hysteresis curves tend to be more rigid-plastic and have very little re-centering, while moment-rotation curves may display the characteristic re-centering tendency. Also, time series for rotation and sliding at the base of the footing should be almost in phase, but should have a different shape.
2. After checking the above, then use the same data files to confirm that the time series data is consistent with the *Summary Performance Results* data, and *Key Plots* provided in the database. For example, the incremental residual rotation using the time series data files should be the consistent with the incremental residual rotation listed in the data table (small deviations possible due to window used for averaging).

It is important to note that methods used to determine the analytical rocking system properties (*FS*, A/A_c, $M_{c\text{-}foot}$) can vary across test series and data contributors. These methods can be conceptually similar but have different details. Since they are based on available literature and their assumptions are consistent with data reported in the database, these differences were considered acceptable and were not part of the data curation process.

HOW TO CITE THIS WORK

If your work heavily relies upon a small subset of the experimental data in the database (i.e. data from one or two test series), it is strongly recommended that, in addition to citing the *FoRCy* database (detailed citation for the database provided at the end of the page), you also cite that particular project(s) using the citation(s) listed in the database.

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Please submit questions or comments regarding this database by using the Questions tab in this page, or by email to Manouchehr (Manny) Hakhamaneshi (manny.hakha@gmail.com), Andreas Gavras (andreasgavras@gmail.com), or Bruce Kutter (blkutter@ucdavis).