

# Towards performance-based seismic design of integrated foundation-structure systems considering soil-foundation interface nonlinearity

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**ABSTRACT:** Dynamic soil-foundation-structure interaction can affect the seismic response of buildings, introducing additional flexibility, radiation damping, uplift, plasticity at the soil-foundation (SF) interface and both transient and permanent relative movements in the foundation soils/support. While research findings are often contradictory on whether these phenomena result in beneficial or detrimental effects, residual tilts, which are the side effects of soil plasticity, can become driving criteria when deciding if the post-earthquake repair of a building is economical or not. As such, current design recommendations suggest supposedly conservative safety factors, and implicitly assume that the foundation soils remain in the elastic domain of deformations.

However, recent earthquakes have shown that in relatively soft soil and during large seismic events, high nonlinearities at the SF interface are unavoidable, causing unexpected failure mechanisms and unplanned repair costs, which in some cases may lead to demolition and thus to significant disruptions. On the premise that such losses could be avoided, this paper aims to introduce SF interface nonlinearity in the seismic design of buildings as part of an integrated approach, where the performance of both foundation and structure are considered.

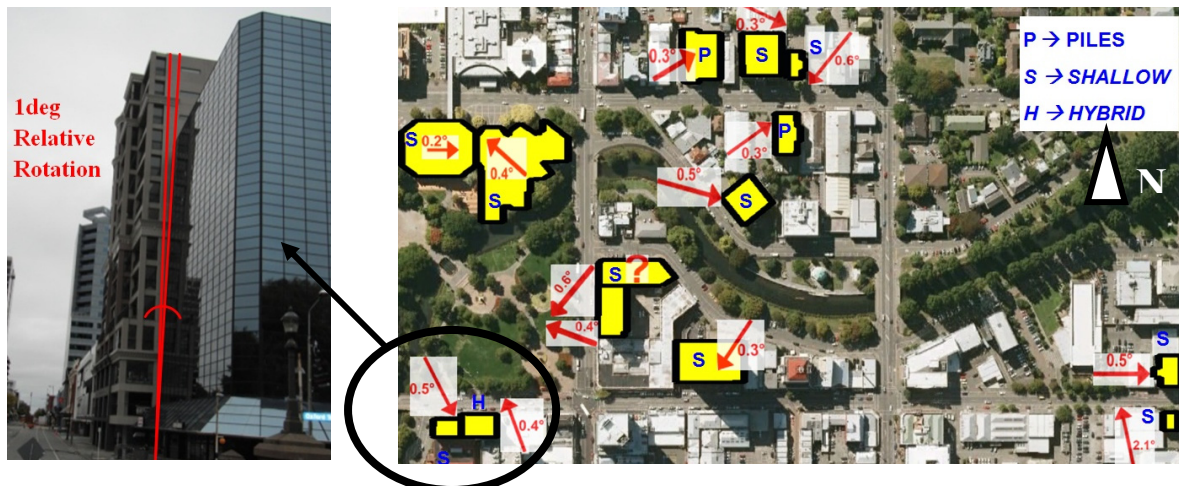
In this context, a performance-based integrated framework based on a combination of maximum and residual responses of both foundation and structure is proposed. Discussion is provided regarding the limit states to be adopted and the needed critical input. A case study from the Christchurch earthquake is used to show that the combined foundation-structure damage caused the building to be demolished, highlighting the need of considering such aspects during the everyday design practice.

## 1 INTRODUCTION

It is well known that during large seismic events and in relatively soft soils, the seismic response of buildings can be significantly affected by flexibility at the soil-foundation (SF) interface, which imposes additional transient displacements at the structural level and is able to amplify or reduce the structural demand depending on the period shift caused by this additional flexibility. Most importantly, this dynamic soil-foundation-structure interaction (SFSI) is often accompanied by uplift and soil plasticity, capable of further amplifying/modifying the structural response; the former tends to re-centre the system, while the latter causes permanent global and differential settlements. As a result of a trade-off between these two interaction effects, a building may suffer significant residual tilt and/or settlement, failing to some extent its basic service criteria or, in the worst case scenario, the imposed additional displacements combined with second order effects may trigger its overturning, putting at risk people lives. Also, differential settlements may cause distress in the superstructure, eventually leading to failure of structural members.

As the occurrence of the described failure mechanisms depends on a number of factors such as ground motion characteristics, soil type and its distribution beneath the building, foundation and superstructure layouts, controlling such phenomena is considered a challenging task and, as such,

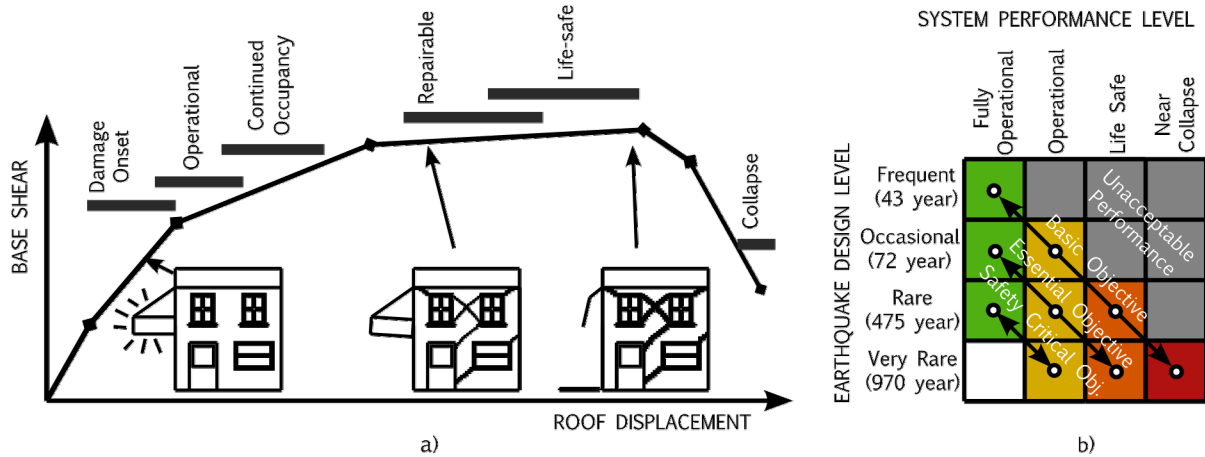
current design recommendations suggest supposedly conservative safety factors, implicitly assuming that the foundation soils remain in the elastic domain of deformations. However, experience has shown that, during large seismic events and in relatively soft soils, high nonlinearities at the SF interface are unavoidable, resulting in ground failure and high rehabilitation costs which, combined with the conventionally accepted structural damage, may rationally lead to demolition of the building and consequently to significant disruption costs. After the Christchurch 2011 event, for example, extensive damage to the built environment was recorded (Cubrinovski et al., 2011; Kam et al., 2011), including many cases in which effects of combined structure-foundation failures (or either structure or foundation dominated) were observed. Both the central business district (CBD) and residential suburbs were largely affected by widespread demolitions, which caused an enormous economic and social impact on the second largest city in the country. **Figure 1** shows the extent of such effects through an enlargement of Christchurch CBD, where selected multi-storey buildings have been highlighted along with their foundation types and residual tilts: as a matter of fact, eleven out of those fourteen buildings have been demolished. It is thus apparent that, in such cases, a proper seismic design should consider the performance of the overall foundation-structure system, comprising of target performances at both the structural and foundation or system levels. This would also allow the implementation of a new design philosophy in which soil is exploited as a source of energy dissipation during seismic events through rocking or sliding of foundations (e.g. Gazetas, 2006; Anastasopoulos, 2009; Liu et al., 2013). As “the strength of a chain is the strength of its weakest link” (Paulay and Priestley, 1992), the soil performing in nonlinear range could become a fuse in the load path, totally or partially ‘saving’ the structure from excessive acceleration and interstorey drift demand to the detriment of permanent displacements at the foundation level; given that, as above mentioned, these collateral effects are sometimes unavoidable and that a proper performance control would result in an optimized structural design, these concepts support the idea that an integrated soil-foundation-structure performance-based assessment and design is the obvious target for the future of seismic design.



**Figure 1. Residual tilts observed in Christchurch CBD after the February 2011 earthquake (Giorgini et al., 2012).**

Performance-based earthquake resistant design (PBD) evolved beyond ‘collapse prevention’ principles into a design philosophy aimed to control the structural performance under different seismic intensities, preventing human life losses in exceptional events and minimizing damage and thus disruption after small to medium events, such that economical losses are contained within limits proportional to the seismic intensity and structure importance (Hamburger and Mohele, 2000). A conceptual PBD framework was developed by SEAOC's Vision 2000 Committee (OES, 1995) and is illustrated in **Figure 2**. When a structure is loaded laterally, as it goes into the nonlinear range (**Figure 2a**), it undergoes increasing levels of damage, called damage states, from negligible to complete (collapse). Setting thresholds in the form of lateral deformation values corresponding to principal damage levels, allows a rational definition of the structural performance. These thresholds are set as ‘fully operational’, ‘operational’, ‘life safe’ and ‘near collapse’. Combining the defined damage states with different seismic hazards at a given site having specified probabilities of occurrence, a

performance matrix is produced (**Figure 2b**); three main performance objectives are defined, namely 'basic', 'essential' and 'safety critical'. Once the performance objective is selected, the performance to be expected under different events is set. This conceptual framework, currently implemented in FEMA356 (2000), quantifies the seismic structural performance (in terms of maximum transient and permanent drifts) and defines the damage to be expected in different structural and nonstructural elements under pre-defined performance levels. The structural members and nonstructural components are considered as independent, meaning that they are not combined in the performance level definition. Foundation performance is listed under the structural element category and independently quantified as total and differential residual settlement.



**Figure 2. PBD approach for structures: (a) Performance levels and relative damage (after Hamburger and Mohele, 2000); (b) Performance matrix of Vision 2000 (reproduced from SEAOC, 1999).**

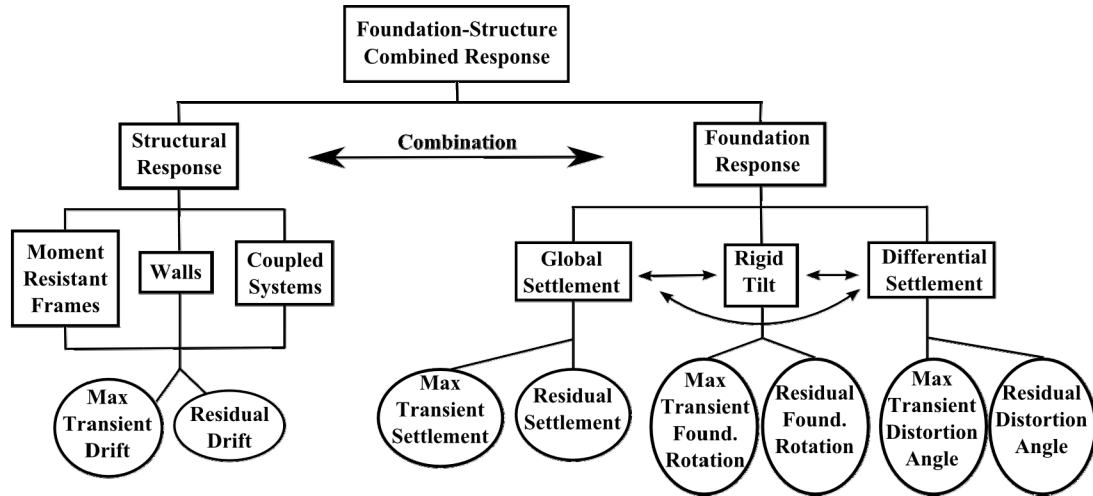
As it is defined, the framework does not take into account the cumulative effect that each damaged component has on the overall system performance. This is especially important in the post-earthquake assessment phase, when the consultant engineer has to decide if repair/rehabilitation is economical or not, or in the context of loss minimization during the design phase, when the owner may want to be assured that eventual disruptions and expenditures will not exceed certain thresholds, and that demolition may only be necessary after certain earthquake events, according to the case specific needs. In the light of these observations, it is envisaged that PBD should be carried out by considering the combined performance of different components of the overall structure-foundation system and defining a global damage index, able to express the actual damage level. While a modified PBD framework comprising of nonstructural elements and structural residual deformations has been already proposed by Pampanin et al. (2002) and Christopoulos et al. (2003), integrated foundation-structure systems have not been addressed yet. In the following, a performance-based design framework is thus proposed for the integrated foundation-structure systems.

## 2 PROPOSED FRAMEWORK

### 2.1 Framework overview

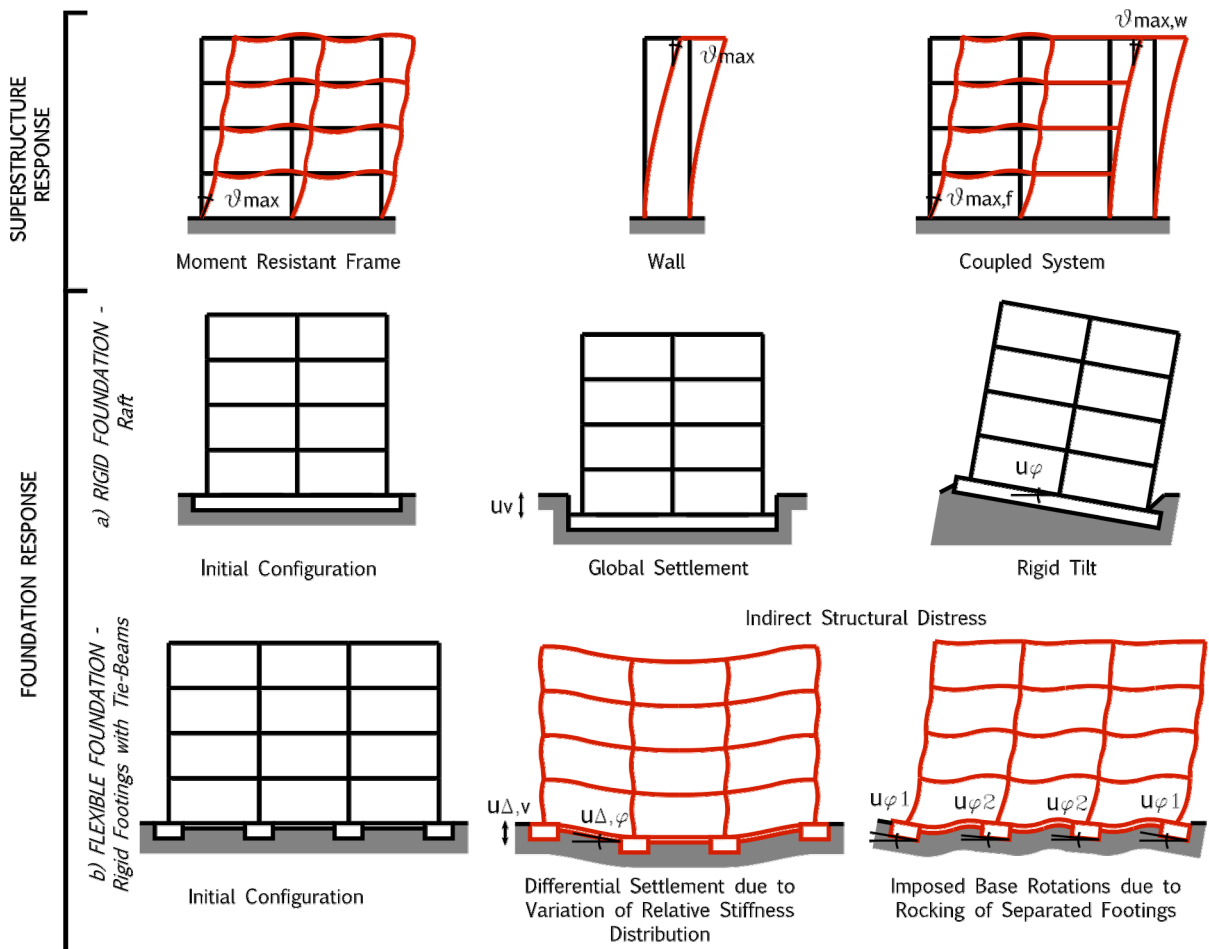
The overall performance of a foundation-structure system can be described as rational combinations of structure and foundation response parameters. As shown in **Figure 3**, different structural systems (moment resistant frames, walls, coupled systems) can be associated to a combination of different soil-foundation interface responses (rigid tilt and differential and global settlement), due to nonlinear behaviour of soil material. While the structural response is a measure of the deformation demand directly occurring in the structure as it was fixed at the base, the soil-foundation interface can have direct and indirect effects on the superstructure/system: if the foundation is relatively rigid with respect to the soil, it causes rigid body movements at the base such as global translations and/or rotations but, if the foundation is partially or entirely flexible and the relative stiffness distribution changes during the event due to non uniform soil softening and/or liquefaction, or the foundation pads

are allowed to rock, differential settlements and/or localized rotations may occur imposing distress/deformations/damage to structural members. These effects can be further amplified by an uneven distribution of the overturning moments as a function of the structural layout/characteristics.



**Figure 3.** Flow chart for the performance-based design framework of integrated foundation-structure systems.

Referring to both superstructure and foundation, each response mechanism can be 'quantified' in terms of maximum transient and residual response parameters, e.g. the interstorey drift for the superstructure response ( $\theta$ ), the settlement for global translations ( $u_v$ ), the foundation rotation for rigid tilt ( $u_\phi$ ) and the distortion angle for differential settlement ( $u_{\Delta,\phi}$ ).



**Figure 4.** Summary of potential response mechanisms for structures and foundations (a) rigid, b) flexible).

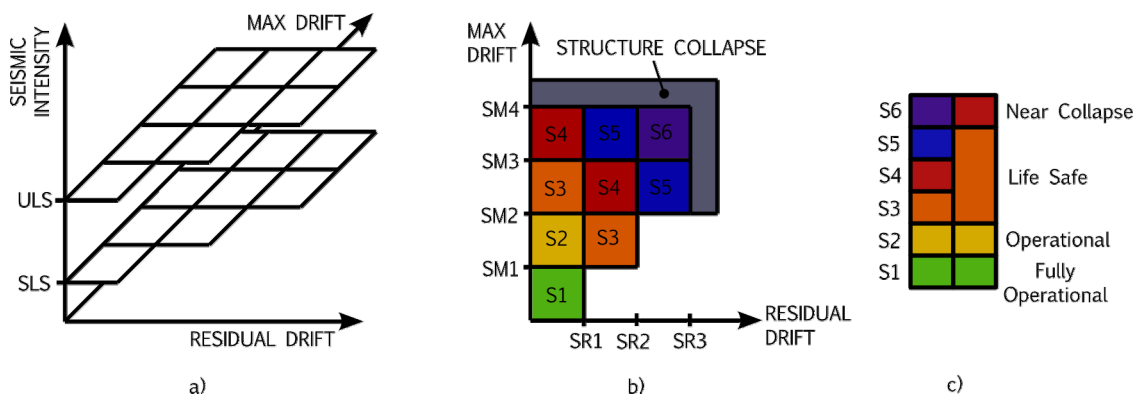
These parameters can then be combined to give global performance limit states. **Figure 4** illustrates the described failure mechanisms for both structural and foundation responses, which may need to be combined depending on the specific superstructure/foundation layout.

Since the proposed performance-based design framework is based on the rational combination of the superstructure and foundation response parameters, the performance of the two components can be separately evaluated and then combined to give foundation-structure (FS) system performance limit states. From the user point of view, this means that once the system limit state is defined, a disaggregation can be performed to allocate target performances to both foundation and structure, according to the selected design philosophy. In the following, structure and foundation performances are first separately analysed and then combined.

## 2.2 Superstructure

For structures, the proposed procedure adopts the performance-based framework proposed by SEAOC (1999), and modified by Pampanin et al. (2002) and Christopoulos et al. (2003), to include structural residual deformations in the definition of target performances. This is because it is felt that, consistently with the integrated proposed procedure, structural residual deformations play a key role in the definition of the structural performance. Excessive residual deformations can increase the cost or impair the reparability of the system as the new at rest position of the building is altered and, to the extreme, they can result in the partial or total loss of the building. Furthermore, such an approach allows the correct performance evaluation of low damage systems, which would not otherwise fit the traditional performance-based framework.

**Figure 5** shows the performance-based framework disaggregated for structures (after SEAOC, 1999; Pampanin et al., 2002; Christopoulos et al., 2003). Combining seismic intensity, maximum and residual drifts, a 3-dimensional performance matrix has been proposed (**Figure 5a**). Different levels of maximum transient and residual deformations (i.e. drifts) are considered, namely ‘SM1’ to ‘SM4’ for the former and ‘SR1’ to ‘SR3’ for the latter. For each seismic intensity, given the two basic parameters, six combined performance levels are set (from S1, green, to S6, purple), such that some of the overall limit states (S3, S4 and S5) can result from different performance combinations; for example, the performance limit state S3 can be given by a combination of maximum and residual drift levels respectively ‘SM2’ and ‘SR2’ or ‘SM3’ and ‘SR1’. Structural collapse happens when ‘SM4’ or ‘SR3’ performance limit states are exceeded. For simplicity, these six structural limit states can be condensed into and reconciled with the four ‘traditional’ performance levels, named according to SEAOC (1999) (**Figure 5c**).



**Figure 5. Performance-based limit states for structures (after SEAOC, 1999; Pampanin et al., 2002; Christopoulos et al., 2003).**

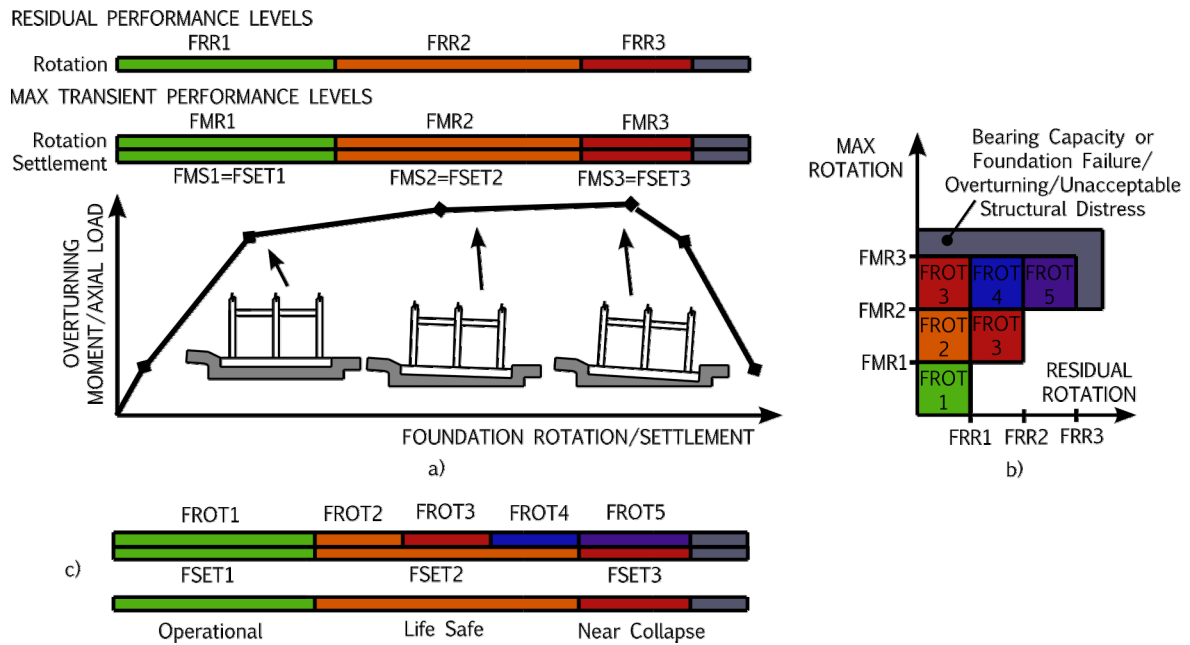
Permissible transient and permanent drifts for different structural systems are reported in FEMA356 (2000), and summarized in Table 1.



## 2.3 Foundations

The performance-based framework disaggregated for foundations is defined in a similar fashion, the difference being that the response parameters to be considered are two, i.e. the foundation global settlement and the foundation rotation (either due to rigid motion or due to differential settlement producing angular distortion). The combination of these response parameters defines the correspondent performance limit states for foundations, to be associated with the structural limit states.

**Figure 6** shows a schematic of the foundation limit states and performance level matrix. As a foundation-structure system founded on flexible soil is loaded laterally (**Figure 6a**), the foundation settles and/or rotates, increasing the level of permanent displacements at the soil-foundation interface. Three limit states are herein suggested for both maximum transient and residual displacements. When considering settlements, the maximum transient values will not significantly differ from the residual ones, thus only the maximum values can be used. The foundation rotation is instead evaluated through both demand parameters, namely the foundation maximum rotation, FMR, and the foundation residual rotation, FRR). Combining residual and maximum rotations, five limit states are set (**Figure 6b**). **Figure 6c** shows the final independent limit states (foundation rotation, FROT1 to 5, and foundation settlement, FSET1 to 3), which for simplicity could be condensed into three main performance levels, according to SEAOC (1999).

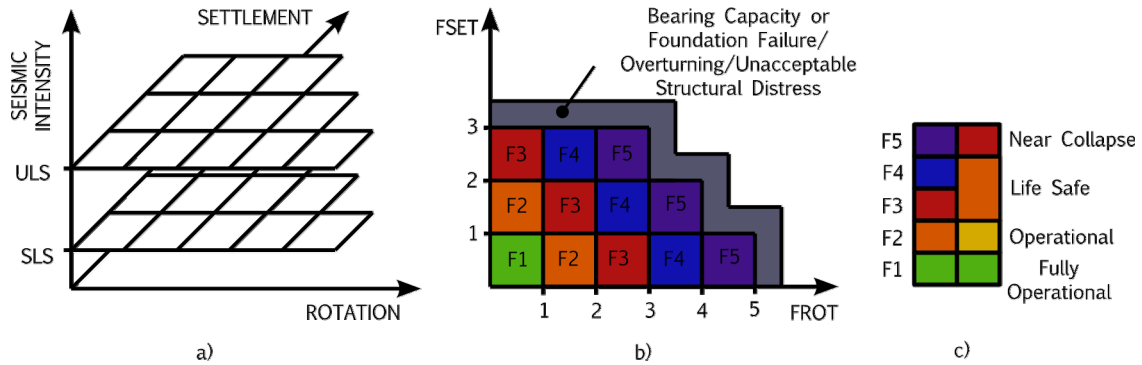


**Figure 6. Performance-based limit states for foundations: rotation and settlement as separated response parameters.**

As foundation rotation and global settlement can occur together, FROT and FSET have then been combined as well, so that a total foundation performance limit state vector  $F$  is defined (**Figure 7**). The combination of settlement and rotation performance levels with seismic intensity results in a 3-dimensional performance matrix (**Figure 7a**). For each seismic intensity, five combined performance levels are set (from F1, green, to F5, purple), such that the total foundation performance worsens as the performance of one of the two parameters reduces (**Figure 7b**). **Figure 7c** shows the total foundation performance vector as simplified according to SEAOC (1999).

It must be noted that for what foundations are concerned, maximum and residual displacements are in most cases a matter of serviceability issues, unless overturning is triggered by liquefaction or dramatic clay softening due to asymmetric load conditions or bearing capacity failure, or the indirect imposed distress on the superstructure causes failure of the structural members at an unacceptable structural limit state. While global settlement is important to control (or evaluate) the functionality of services

(from minor to major damage), rotation may be controlled by (or evaluated against) threshold tilts for immediate occupancy, jacking up and overturning limits if the foundation is rigid, or undamaged, intermediate foundation damage and foundation failure if the foundation is flexible. Since in the latter case structural distress may occur, the limits given by intermediate damage and failure of foundations are to be taken as the minimum between the actual foundation rotation satisfying those limit states and the one resulting in indirect acceptable structural performance limit states. The latter depend on the specific structure-foundation system and are to be evaluated on a case by case basis or defined through extensive parametric analyses.



**Figure 7. Performance-based limit states for foundations: rotation and settlement combination.**

The basic limit states definition can follow different approaches. For example, the Greater Vancouver Liquefaction Task Force (2007), relates the foundation performance to the structural one; assuming that at 2475 and 475 year return period the structural residual deformations are respectively 20% of maximum transient drift and negligible, the foundation residual limit states are respectively set at 80% and 60% of the maximum transient drift ratio at 2475 year return period. Nakano et al. (2004), set instead foundation damage levels (from ‘none’ to ‘heavy’) as a combination of tilt and settlement thresholds (respectively 0.7, 1.3 and 3.3% and 0.05, 0.1, 0.3m). In literature, no indication is found regarding the maximum foundation rotation to be allowed during transient response. It is important to note that the correct definition of the limit states for foundation settlement and rotation is a key component for the reliability of the proposed framework. Although some values and criteria are proposed in literature, the applicability of such limit states should be checked on a case by case basis, so that the adopted values are consistent with the actual building size, specific foundation-structure system and performance requirements.

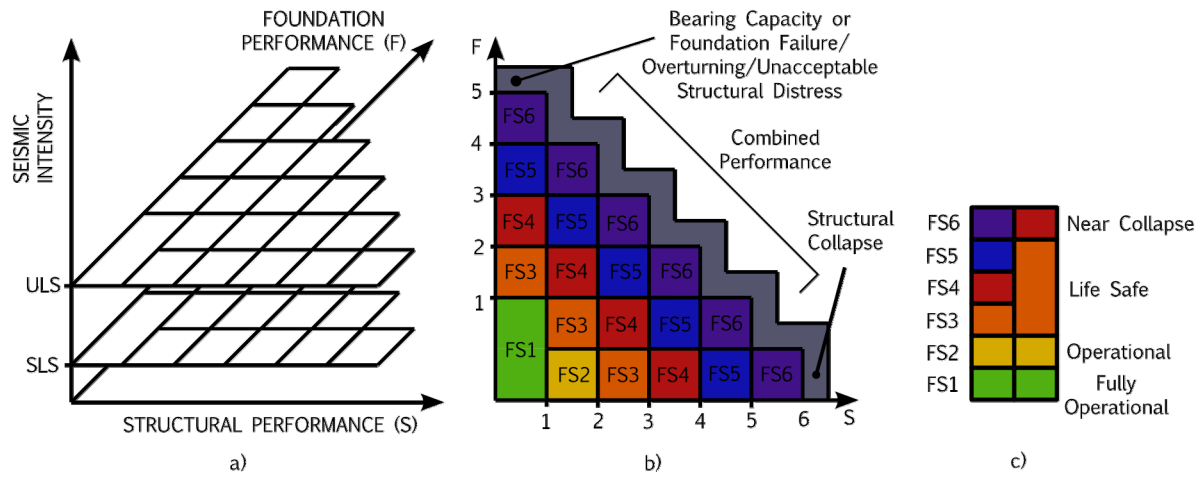
## 2.4 Integrated foundation-structure systems

After having separately defined performance vectors for both structure and foundation, the two arrays are combined to produce an integrated foundation-structure performance matrix (**Figure 8**), which becomes 3-dimensional if associated to different levels of seismic intensities (**Figure 8a**). For each seismic hazard, the global matrix encompasses all the possible structure and foundation performance combinations, including the cases of complete failure of only either structure or foundation (soil side for rigid foundations or member side for flexible foundations) (**Figure 8b**). When superstructure and foundation performances are combined, the integrated performance level worsens. Six integrated performance levels are defined (FS1, green, to FS6, purple). Performance levels beyond 6 are considered equivalent to the complete loss of the building (either actual collapse or need to demolish it).

The integrated performance vector FS is finally condensed (**Figure 8c**) according to SEAOC’s framework (**Figure 2b**), which is still valid in principle. Depending on the importance level of the structure or clients’ expectation, a performance objective is selected, meaning that the seismic design will need to guarantee predefined performance levels (‘fully operational’, ‘operational’, ‘life safe’ and ‘near collapse’) under different seismic hazards (‘frequent’, ‘occasional’, ‘rare’ and ‘very rare’). At this stage, depending on the adopted design philosophy (i.e. where ductility is allocated under different earthquake design levels), the designer can select the most appropriate performance combination of

structure and foundation responses (from S1 to S6 and F1 to F5), to give the selected limit state (FS1, FS2, between FS3 and FS5 or FS6). For each component, the target performance can then be disaggregated as shown in Figures 7, 6 and 5, to perform a seismic design where the response parameters concerning both structure and foundation (maximum and residual structural drift, foundation maximum settlement, maximum and permanent foundation rotation) are controlled since the early design stages.

To implement the above approach, reliable tools are needed to properly (quantitatively) assess the combined response of the building-foundation system. Depending on structural and foundation layout and on soil properties, the sophistication needed in the evaluation may change considerably. For example, for irregular structure-foundation systems founded on liquefiable soil, FEM analyses able to account for pore water pressure variation are needed; on the other side, for a relatively regular structure founded on raft foundations and cohesive soil, numerical analyses carried out through simplified nonlinear models such as the beam-on-nonlinear-Winkler foundation (BNWF) (e.g. Harden and Hutchinson, 2009) or the macroelement formulation (e.g. Gajan and Kutter, 2009; Chatzigogos et al., 2011) may be accurate enough for the needed degree of sophistication. Also, displacement-based design procedures are needed to perform an integrated foundation-structure design able to guarantee a controlled seismic response from both the superstructure and foundation points of view (e.g. Paolucci et al., 2013 and Millen et al., 2014).



**Figure 8. Performance-based limit states for integrated foundation-structure systems.**

## 2.5 A case study from the 2011 Christchurch earthquake

The proposed framework is validated through a case study building which suffered from combined foundation-structural system damage during the 22<sup>nd</sup> Feb 2011 Christchurch earthquake. The building is a 22 storey seismic resistant frame founded on rigid raft foundations. Residual tilts at the column bases representative of the foundation residual differential settlement were measured in March 2011, suggesting a residual tilt in south-west direction of 0.5%. A detailed damage inspection of the exposed structural skeleton and individual members prior to full deconstruction was also carried out in July 2012, suggesting a maximum transient drift in the range 2-3%. Details regarding the building and the observed structural damage can be found elsewhere (Giorgini et al., 2013). Table 1 shows performance limit states adopted for this exercise.

Table 2 summarizes the validation outcome (foundation rotation  $FROT < FROT1$ , foundation settlement  $FSET1 < FSET < FSET2$ , superstructure residual drift  $SR1 < SR < SR2$ , superstructure maximum drift  $SM3 < SM < SM4$ ), which would lead to foundation performance  $F = F2$  (orange), superstructure performance  $S = S5$  (blue) and thus foundation-structure performance  $FS > FS6$  (not acceptable). Looking at these results, the structural damage seems to have contributed the most to the overall performance state, made unacceptable by foundation settlement. Although this is consistent with the final decision to demolish the building, the foundation rigid rotation resulting in a consequent tilt of the building was expected to provide the most significant contribution to the foundation performance, rather than the global settlement which was not very pronounced. The reasoning behind



this interpretation could be summarized as: (i) the adopted settlement limit states were probably too small for a 22 storey building founded on a deep raft; (ii) the actual tilt was likely to be higher than the measured one (the reported tilt was an approximated average value rather than the maximum measured tilt); (iii) for a given tilt, the out of plumb (or residual displacement) of a high-rise building is more critical in terms of post-earthquake response as well as urgency and complexity to proceed with repairing (straightening) than in the case of a low-rise building. This highlights the sensitivity of the proposed framework to the set limit states and the need to consider building-specific target performance levels. By for example changing the foundation rotation and settlement values in Table 1 (decreasing the former and increasing the latter), the building performance would result unacceptable based on the foundation rotation criteria.

**Table 1. Summary of performance limit states used for the framework validation on a case study building**

| Label (F&SR) | Label (SM) | SR*        | SM* | FRR** | FMR*** | FSET**** |
|--------------|------------|------------|-----|-------|--------|----------|
| 1            | 2          | Negligible | 1%  | 0.70% | 0.70%  | 0.05m    |
| 2            | 3          | 1%         | 2%  | 1.40% | 1.40%  | 0.1m     |
| 3            | 4          | 4%         | 4%  | 2.80% | 2.80%  | 0.3m     |

\*Superstructure residual (SR) and maximum (SM) drifts according to FEMA356, where the first performance level is ‘Immediate Occupancy’, corresponding to SEAOC’s ‘Operational’ limit state; \*\*Foundation residual rotation calculated assuming  $FRR=0.7*SM$  (defined combining Greater Vancouver Liquefaction Task Force, 2007 and Nakano et al., 2004 approaches); \*\*\*Foundation maximum rotation assuming that  $FMR=FRR$ ; \*\*\*\*Foundation global settlement according to Nakano et al. (2004)

**Table 2. Summary of performance-based assessment data used for the proposed framework validation (bold: estimated values, italic: adopted performance limit states)**

| FRR               | FMR               | FSET*                    | SR**                  | SM                |
|-------------------|-------------------|--------------------------|-----------------------|-------------------|
| <b>0.5%</b> <0.7% | <b>0.5%</b> <0.7% | 0.05m< <b>0.1m</b> <0.1m | 0.5%< <b>0.9%</b> <1% | 2%< <b>3%</b> <4% |

\*Estimated but not clearly observed; \*\*SR=0.3\*SM

### 3 CONCLUSIONS

A performance-based design framework for integrated foundation-structure systems has been proposed. Starting from the SEAOC performance-based approach, the proposed procedure would allow to perform seismic design/assessment taking into account the performance of both foundation and structure, through a disaggregation process which leads to the explicit definition of maximum transient and residual displacements of both components. Performance states are defined by combining the damage of components and response parameters, so that the final performance state FS is a measure of the system global damage. A case study from the Christchurch 2011 earthquake has confirmed that, with properly defined limit states, the combination of structural maximum transient and residual drift and foundation rotation would lead to a global level of irreparability and thus its demolition even if the individual damaged components were arguably technically repairable.

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