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EVALUATION SYSTEM OF SESMIC CAPACITY FOR BUILDING FOUNDATIONS AND CASE STUDIES ON BUILDINGS IN SENDAI CITY

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ABSTACT: The authors have developed a systematic approach for the seismic evaluation of building foundations. The proposed approach allows structural engineers to choose between an empirical based, relatively simple method, and a theoretical, more rigorous method involving numerical seismic response analysis, as may be appropriate for the seismic evaluation of foundations. Applicability of this approach is verified in the case study of some buildings in Sendai city, which suffered damage to their foundations during the 1978 Miyagiken-oki Earthquake and the 2011 Great East Japan Earthquake.

Key Words: Building Foundation, Seismic Evaluation, Great East Japan Earthquake

INTRODUCTION

Following the 1995 Hyogoken-Nanbu Earthquake, it has been a common practice in Japan to conduct seismic evaluation of existing buildings. However, evaluation of the seismic capacity of foundations and soils supporting existing buildings has been generally disregarded because the regulations governing the practice do not provide adequate procedure for this purpose. Meanwhile, during the 2011 Great East Japan Earthquake, there were several cases reported where operation or regular occupation of buildings had to be suspended because of the damage to foundation supporting the building.

The authors have studied the requirements for foundations and supporting soils to provide resistance against the design earthquakes associated with the level of performance, and evaluated analytical methods to estimate seismic capacity of foundations. As a result, a systematic procedure to evaluate the seismic capacity of building foundations necessary to maintain structural function, even after major earthquakes, is evolving.

This report presents a basic procedure for seismic evaluation of existing building foundations and discusses its applicability to some buildings in Sendai city damaged during the 2011 Great East Japan Earthquake.

SEISMIC EVALUATION OF EXISTING FOUNDATIONS

In general, the Japanese structural design codes do not require the building foundations to remain undamaged under extreme seismic events. This is based on the premise that damage to building foundations is unlikely to cause the risk to life from catastrophic collapse of superstructure. However, it is possible that the failure of foundation system may have resulted in life loss in some cases where the soil liquefaction was a factor in the collapse of superstructures during the 1995 Hyogoken-Nanbu Earthquake. The authors feel that a thorough seismic evaluation of existing buildings should include an examination of the foundation, and assessment of the capability of the soil beneath the foundation to withstand seismic forces. Even when the superstructure has sufficient seismic capacity, a tilted building owing to foundations damage will result in loss of function and property value. Besides, such buildings will become obstacles to emergency evacuation.

Thus, it is necessary to conduct seismic evaluation of superstructures as well as foundations to ensure required performance. Authors have taken this initiative to propose the seismic evaluation procedure so that the seismic evaluation of building foundations can be performed routinely in practice.

This evaluation procedure is expected to be applicable to the buildings and ground conditions mentioned as follows:

1) Buildings for which the seismic evaluation of superstructure has been conducted in advance. It is not expected to be applicable to building that have collapsed or tilted due to the foundation damage. The operational performance can be guaranteed by examining as a total system consisting of the foundation and the superstructure.

2) Buildings designated as emergency hospitals and evacuation facilities, and those facing designated evacuation routes. In these cases tilting of buildings can jeopardize their function, or may become a hazard to mass evacuation.

3) Sites where liquefiable soils or very soft deposits exist, regardless of the building type. In these soil conditions, total failure of supporting soil may cause the building to overturn.

In addition, the seismic design of foundations has not been considered in most buildings constructed before 1980s in Japan. It is reported that a considerable number of those buildings were damaged due to foundation failure during the 1995 Hyogoken-Nanbu Earthquake. Similar trend can be expected for Tohoku area in relation to the 2011 Great East Japan Earthquake. Need for seismic evaluation of such building foundations is anticipated as the recovery and reconstruction efforts continue.

Seismic evaluation of buildings including foundations will also provide the building owners with adequate understanding of the expected performance of their buildings under a design earthquake, considering functional as well as safety aspects.

PROPOSED PROCEDURES FOR SEISMIC EVALUATION OF FOUNDATIONS

The target performance level of foundations is to ensure safety of occupants without failure of the buildings and/or to maintain them in operational condition such that excessive tilt and/or displacement do not impact functionality. Three nonstructural performance levels for buildings defined in the seismic evaluation procedure are shown in Table 1. In consideration of the importance and function of the building, professional engineers can choose an appropriate level of performance corresponding to a design earthquake from Table 1.

Structural damage conditions of foundation members associated with corresponding performance levels in Table 1, which are called limit states, are described in Table 2. It is noted that the relationship between the damage of foundations and possible excessive settlement and/or tilting of foundations is not clarified, for which further study is necessary.

Table 1. Nonstructural Seismic Performance Levels of Buildings

A: Operational Level	**B**: Immediate Occupancy Level	**C**: Life Safety and Collapse Prevention Level
All basic structural functions are preserved. Continued use is possible without repairs, and no excessive displacement and deformation has occurred.	Continued use of the building is possible if feasible repairs are performed, but no excessive displacement and deformation has occurred.	Entire structure is still stable despite the loss of bearing capacity, and overturning or collapse has not occurred.

Table 2. Correlation between the Level of Performance and the Relevant Limit State of Foundation

	A	**B**	**C**
Foundation Soil	Bearing capacity and displacement does not exceed ther yield level values by more than two fold, both in push and pull directions.	Bearing capacity and displacement do not exceed half of their ultimate values in both push and pull directions.	Bearing capacity as well as displacement does not exceed their respective ultimate values in push and pull directions.
Foundation Members (pile, foundation beam, pile cap)	Yield bending moment is not exceeded in more than half the members, and allowable shear strength not exceeded anywhere in all members.	Yield bending is not exceeded in all members, ultimate moment is not exceeded in half the members, and ultimate shear stress is not exceeded in more than two places.	Moment curvature does not exceed limit level, or ultimate moment is not exceeded at two points along depth, and ultimate shear strength is not exceeded in more than half of members.

PROPOSED EVALUATION PROCEDURE

The authors propose a seismic evaluation procedure for building foundations consisting of the following components:

1) Preparatory Decision 1: Verification of the requirements of target building

2) Preparatory Decision 2: Choice of the evaluation method

3) First Level Seismic Evaluation: Estimation by the indices, namely seismic index I_{sf} and the judgement index I_{s0f}, based on the damage investigations in past earthquakes

4) Second Level Seismic Evaluation: Assessment based on static analysis

5) Special Evaluation: Assessment based on dynamic analysis, finite element method or other methods depending on particular conditions

6) Considerations of the need and suitability of seismic retrofitting

The proposed approach allows professional engineers to choose an adequate method for the seismic evaluation of foundations, which can be either an empirical, relatively simple method or analytical, more sophisticated methods such as numerical seismic response analysis and FEM analysis.

Professional engineers perform the seismic evaluation of building foundations following a process shown in Figure 1. Prior to conducting a seismic evaluation, the necessity for the seismic evaluation is judged in the Preparatory Decision 1. Then, a suitable method should be chosen depending on the building conditions in the Preparatory Decision 2. Possible judgment examples at this stage are proposed in Table 3. For instance, the First Level Seismic Evaluation can be applicable for the buildings with shallow foundation or with basement since better near surface ground condition is expected in these cases. On the contrary, the buildings on pile foundations in very soft ground condition, or in liquefiable ground condition, should have Second Level Seismic Evaluation for a more detailed assessment.

The First Level Seismic Evaluation has been proposed based on the seismic indices derived from the failure investigations following the 1995 Hyogoken-Nanbu Earthquake and the required bearing capacity of building foundations (Maruoka et al 1999). As an empirical method, the possibility of the failure of foundation can be roughly estimated in this evaluation. However, no details about how the deficiencies are distributed within the foundation system are provided by this method. The results of evaluation in this method may not necessarily lead to a definite conclusion concerning the requirement for taking further steps. However, professional engineers can employ more sophisticated dynamic analysis, or static non-linear (pushover) analysis, depending on their judgment concerning structural conditions and the expected improvement in the accuracy of performance evaluation by such analyses.

Figure 2 shows possible analytical models for static analysis of pile foundations in the Second Level Seismic Evaluation. Analytical results from such models should be compared to the level of performance in each limit states shown in Table 2. Possible deficiencies in the foundation can be evaluated in more detail in this manner, and one can assess the results to see if they meet the expected performance. Professional engineers can design adequate seismic retrofit to meet performance requirement.

In general, there are two values required for computing pile capacity, namely the lateral load at the pile head and the stresses generated by differential movement of soils. The differential movement in soils can be evaluated from the ground response analysis under site-specific design earthquake.

The seismic lateral load at the pile head should be calculated in the following manner depending on the targeted level of performance:

1) To ensure that the foundation will not fail before the superstructure, the bearing capacity should be sufficient to resist forces transferred from the superstructure under design earthquake.

2) To ensure that the foundation will not collapse under the largest expected earthquake, the bearing capacity should be adequate to resist forces obtained from the response analysis of superstructure under site-specific largest expected earthquake.

In the case of special conditions, such as buildings near slopes, rigorous method, for instance FEM analysis, may be required for proper estimation of seismic forces. Furthermore, dynamic analysis or combined analysis taking soil-pile-structure interaction into account may be necessary. In the seismic evaluation procedure presented, these methods are indicated as appropriate. Choice of an appropriate method is crucial depending on design conditions; this process is regarded as Special Evaluation.

If the results of either the Second Level Seismic Evaluation or the Special Evaluation do not meet the level of performance, a seismic retrofit will possibly be required. In assessing the retrofitting process, it is necessary to consider installation aspects under specific site conditions.

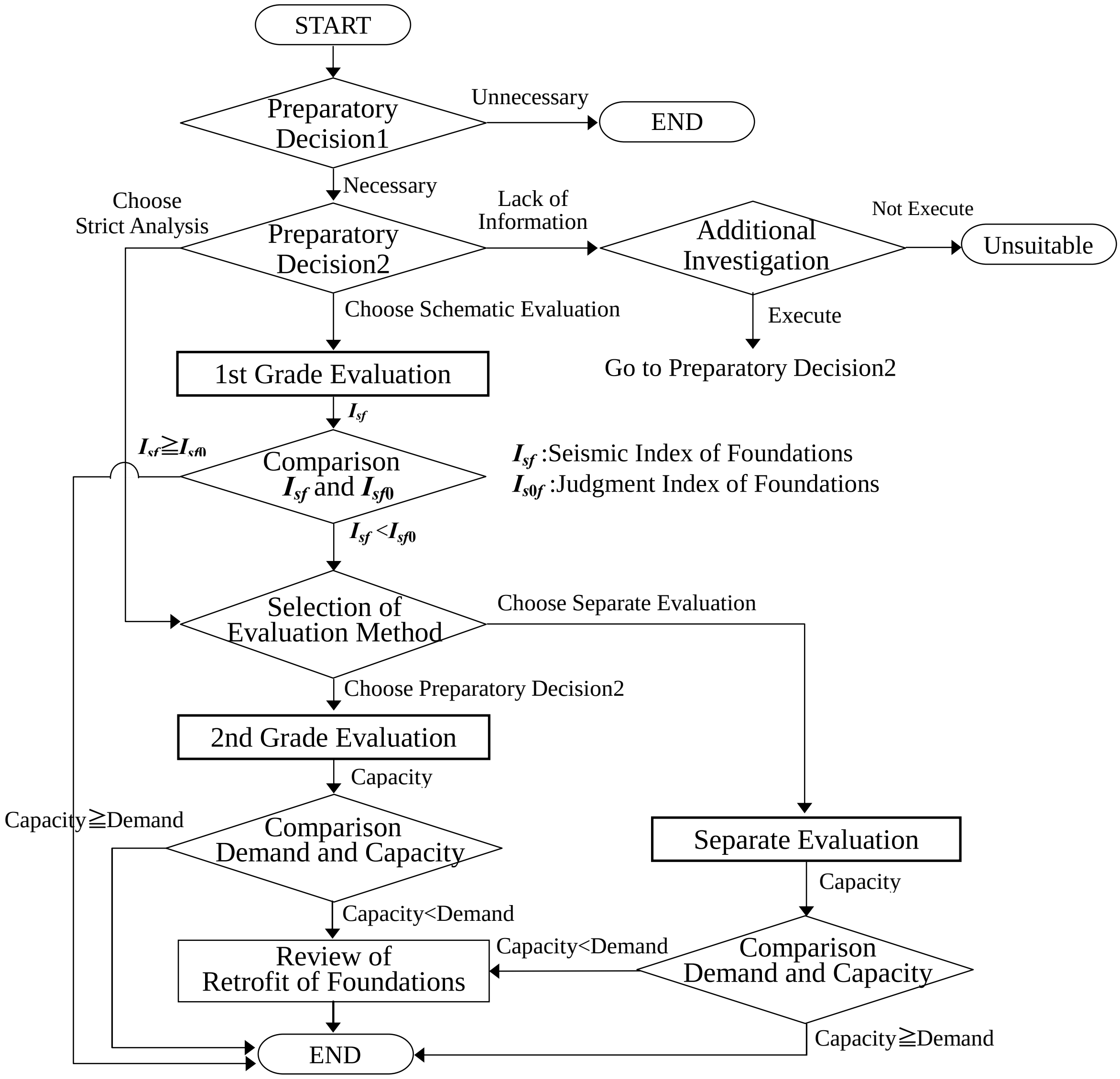


Fig. 1 Flow Diagram for the Seismic Evaluation

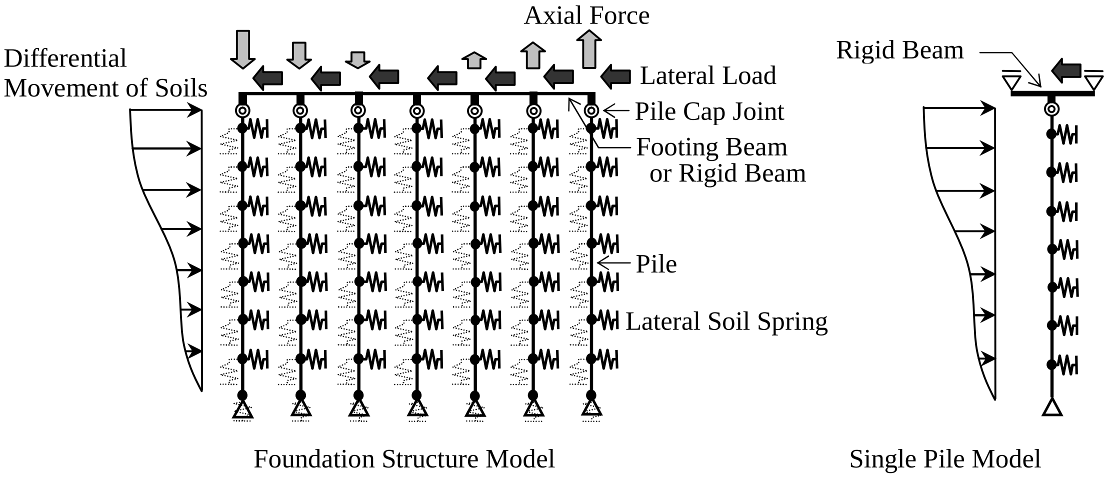


Fig. 2 Analytical Models to evaluate the Seismic Capacity of Foundations

Table 3 Possible Options in the Preparatory Decision 2

Foundation Type	Ground Condition	First level Evaluation	Second Level Evaluation	Special Evaluation
Shallow Foundation	Stable	◎	×	○
	Unstable	×	×	◎
Pile Foundation with basement	Stable	◎	◎	○
	Unstable	×	△	◎
Pile Foundation without basement	Stable	○	◎	○
	Unstable	△	◎	○
	Slope	×	△	◎

◎:Recommended, ○:Usable, △:Usable but not recommended, ×:Not capable

CASE STUDIES

The proposed procedure was applied in the following buildings damaged during the 2011 Great East Japan Earthquake.

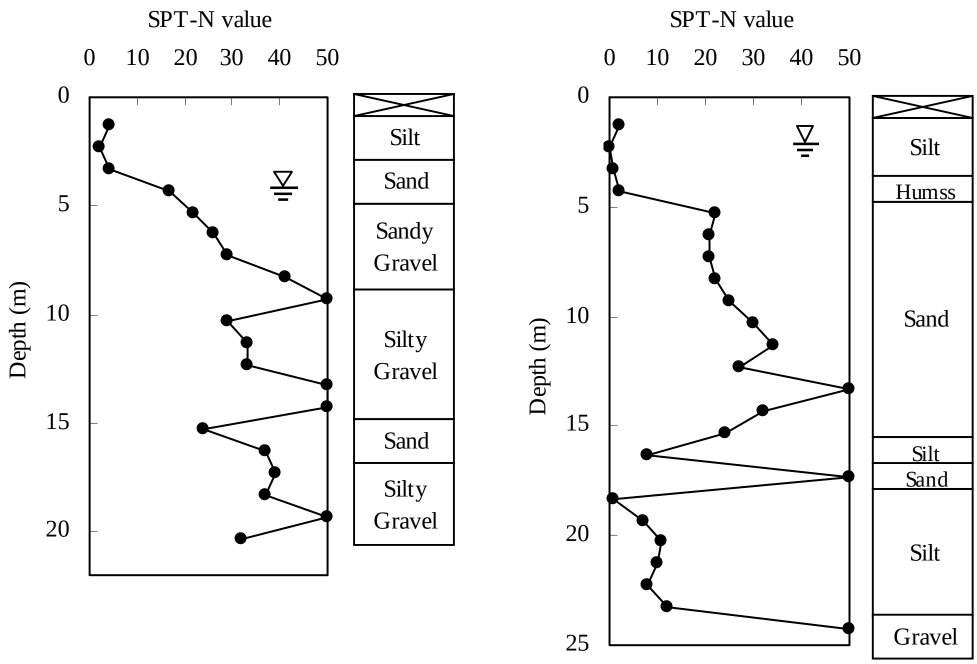
The seismic evaluation was conducted for three apartment buildings located in Sendai city (Sugimura and Oh-oka 1981, Shiga 1980, AIJ 2011a). General information on the upper structures and foundations are given in Table 4. Since these buildings were constructed before 1980s, no effective seismic design was implemented. Soil profiles are shown in Figure 3. Ground condition can be considered relatively stable. It is anticipated that the liquefaction resulting in total bearing capacity of foundation would not occur even though partial liquefaction may occur.

The investigation shows that all of the pile foundations of these buildings had been damaged during the 1978 Miyagiken-oki Earthquake. In building-A, more than half of the piles had been failed either in compression or in shear at pile head. In building-C, although no tilting was observed, the corner piles suffered similar failures near pile head. Building-B, adjacent to the building-A, also showed no tilting while some cracks were identified in some of the piles from a partial investigation.

Subsequently, total retrofitting was carried out for the foundation of building-A. One of the building foundations was converted from the pile foundation to the shallow foundation. Elsewhere, all the failed pile heads were reinforced by means of steel plates, including corner piles of building-C.

Table 4 General Information on Upper Structures and Foundations

	Structure	Number of Stories	Year of Construction	Pile Type	Pile Diameter
A	SRC	11	1978	Precast Concrete Pile	600mm
B	RC	5	1977	Precast Concrete Pile	400mm
C	SRC	14	1976	Precast Concrete Pile	500-600mm



Site of Buildings-A and B Site of Building-C

Fig. 3 Soil Profiles(Sugimura and Oh-oka 1981, Shiga 1980)

Buildings-A and B have remained occupied without deficiency after the 2011 Great East Japan Earthquake. In case of building-C, although upper structure consisting of columns and beams did not indicate any structural damage, it has tilted significantly and is designated as deficient for immediate occupancy. It should be noted that foundations of these buildings have not been investigated following the 2011 Great East Japan Earthquake.

Seismic evaluation of these building foundations was conducted by the proposed procedure. Evaluated index I_{sf} from the First Level Seismic Evaluation are shown in Table 5. The I_{s0f} index value of 0.8 is assessed based on the 1995 Hyogoken-Nanbu Earthquake, The index value requires to be corrected for the maximum acceleration, which is 250.9 gal comparing to 350 gal (considered to be a benchmark) for the 1995 Hyogoken-Nanbu Earthquake. Therefore, the I_{s0f} index value for the 1978 Miyagiken-oki Earthquake would be 0.8*250.9/350=0.57. The three building foundations are categorize as “not good” considering seismic capacity with I_{sf}/I_{s0f}<1.0, which is in agreement with the actual failure situation that occurred at the 1978 Miyagiken-oki Earthquake. However, no details of damage condition are represented in this method.

Table 5 Results of The First Level Seismic Evaluations of Building Foundations in Sendai

	I_{sf} Value	I_{s0f} Value for the 1978 Earthquake	Evaluation Results	I_{s0f} Value for the 2011 Earthquake	Evaluation Results
A	0.33	0.57	not good	-	-
A (After Retrofitting)	0.82	-	-	0.73	good
B	0.28	0.57	not good	0.73	not good
C	0.26	0.57	not good	0.73	not good

Second Level Seismic Evaluation was conducted for buildings-A and B considering the observed seismic motion at the 1978 Miyagiken-oki Earthquake for estimating pile head load and differential deformation of soils. Evaluated results indicate that the immediate occupancy will be unlikely due to the pile head yield in building-A, whereas the foundation of building-B may maintain its function without significant damage. From these results, the foundations of building-A were evaluated to be unsatisfactory at performance level B (Immediate occupancy level), while building-B is regarded satisfactory at level B. The difference of the damage mainly depends on axial force applied to piles by the seismic motion.

Next, retrofitted foundation of building-A was considered for First Level Seismic Evaluation. The I_{sf} index value after retrofitting is estimated as 0.82 and the I_{s0f} index value for the 2011 Great East Japan Earthquake is assessed as 0.73 (corrected for maximum acceleration of 317.7 gal observed in the same building during the 1978 Miyagiken-oki Earthquake (AIJ 2011b). The ratio of I_{sf} to I_{s0f} becomes 0.82/0.73=1.15 and the foundation is categorized as "good".

Through the above-mentioned case studies, the proposed procedure shows results consistent with observation, indicating its applicability for seismic evaluation of building foundations.

CONCLUSIONS

This paper describes the procedure for the seismic evaluation of building foundations with a focus on maintaining buildings in operational level of performance. This procedure allows professional engineers to choose an appropriate method depending on the level of performance and local site condition. Applicability of this seismic evaluation procedure has been verified through case studies on buildings that suffered foundation damage during past earthquake.

Preliminary observations following the 2011 Great East Japan Earthquake indicate that there are several buildings became functionally deficient for occupation due to foundation damage even though the superstructure did not suffer significant damage. These observations indicate the importance of assessing the seismic capacity of building foundations. Authors hope that the seismic evaluation of building foundations following the procedure proposed herein will be more common in Japan.

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