



Seismic Behavior for Reinforced Concrete Building due to Foundation Settlement on Different Soil Types

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Abstract

Reinforced concrete buildings may be harmed by earthquakes, which also frequently result in fatalities. In addition to earthquakes, foundation settlement can also damage building structures, particularly those constructed in soft soil conditions. This paper investigates the effect of foundation settlement and soil type on the seismic behavior of reinforced concrete buildings. Therefore, ten models of reinforced concrete buildings were analyzed based on response spectra. Lateral displacement, inter-story drift, and internal forces of buildings are compared according to foundation settlement and soil type. This present study concluded that foundation settlement affects the seismic performance of RC buildings. The results show that the value of the inter-drift ratio surpasses the permitted limit in all models when the foundation settlement occurs, especially in the X-negative direction. Due to a foundation settlement, the shear force on column C2 and the moment on beam B1 both suffered considerable increases of more than 10%. In the static analysis, the largest internal force does not always occur in soil conditions with soft soil.

Keywords Foundation settlement · Soil type · Reinforced concrete · Seismic performance

1 Introduction

Throughout history, earthquakes have caused collapses and human casualties. Recent earthquakes, such as the 2017 Iran-Iraq earthquake, the 2018 Sulawesi earthquake and tsunami in Indonesia, the 2019 Albania earthquake, the 2020 Aegean Sea earthquake in Greece, the 2021 Haiti earthquake, and the 2022 Afghanistan earthquake, have demonstrated the continued loss of life and property. Indonesia is located between two major tectonic plates, the Australian Plate and the Eurasian Plate. Other than the Sulawesi earthquake, Indonesia has experienced several major earthquakes, including the 2004 Indian Ocean earthquake and tsunami in Aceh, the 2006 Yogyakarta earthquake, the 2009 West Java earthquake, the Sumatera earthquake, the Lombok earthquake, and the 2022 Cianjur earthquake. Because of the significant hazards caused by the earthquake, the structural

performance and life safety of reinforced concrete buildings in Indonesia were to be prioritized. This tragedy has also given a very big challenge to the nation, especially in the construction industry, to come up with an analysis and design of structures that can withstand seismic loading (Hong et al. 2020). Therefore, it is important to consider seismic loading in the design of reinforced concrete buildings, especially for a building whose seismic resistance is of importance in view of the consequences associated with a collapse, such as an office and research laboratory building. The seismic performance of a building is influenced by the soil types, where the foundation soils are one of the main elements in performing a correct seismic design for structures (Galal and Naimi 2008; Jiang et al. 2012; Majid et al. 2017; Yön and Calayir 2015; Zebua and Wibowo 2022).

Some studies on soil-structure interaction include little to no information on how the building reacts to the varying settlement of the foundation. While excessive and uncalculated settlements may frequently happen throughout the lifespan of the construction, foundation settlement can be expected at the design stage (Hong et al. 2020). This is mostly the result of modifications to the loads and environmental factors, such as nearby new development

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(Mohammed et al. 2013), deep excavation (Camos et al. 2014), heavy flooding, or earthquakes (Son and Cording 2011). A ten-story reinforced concrete building that had its foundation differentially settled by 25 mm was the focus of an investigation by Lin et al. (2016). According to Indonesian National Standard 8460 (Badan Standardisasi Nasional 2017), for high-rise buildings, the value for the permitted differential settlement was recommended at less than 15 cm plus the width of the foundation (b) in centimeters divided by 600, as long as it could be demonstrated that the upper structure is still safe.

Meanwhile, Indonesia is located between two major tectonic plates, the Australian Plate and the Eurasian Plate. On September 2, 2009, the West Java region of Indonesia was struck by a MW 7.3 earthquake, one of the strongest in recorded history, and some areas were affected, including Bandung city, where the studied 3-story building is located. Furthermore, the Lembang fault is located nearby in the province of West Java. Based on the PUSGEN map, the Lembang fault is one of 81 active faults in Indonesia (Irsyam et al. 2018). Fig. 1 shows Bandung city and the Lembang fault location.

In this study, the effects of local soil conditions and foundation settlement have been evaluated. The aim of the study was also to evaluate the interaction between soil condition and structure, such as the lateral displacement, inter-story drift, and internal forces of the reinforced concrete office

and research laboratory building, which have been studied in this research.

2 Methods

2.1 Structure Related Data

The structure used in this research is a three-story reinforced concrete office and research laboratory building. This building is an existing structure built in the early 1980s and located in Bandung, Indonesia. The layout and elevation of the building are shown in Fig. 2. The building measures 25.2 m in longitudinal directions with an additional 2.4 m, 14.4 m in transverse directions, and 3.6 m in story height. There are eight longitudinal frames (numbered 1–8) and four transverse frames (designated A–D). The longitudinal spans are 3.6 m. There are three types of spans in the transverse direction: 4.8 m (A–B), 2.4 m (B–C and 8–9) and 7.2 m (C–D). The building's lateral load-resisting system is made up of reinforced concrete moment-resisting frames (RC-MRF) in both directions. The roof is constructed by steel frames with a span of 14.4 m. The concrete compressive strength $f_c' = 30$ MPa and the reinforcement yield strength $f_y = 300$ MPa were used in the analysis. The geometry of the structures involved in the study, along with the various details of the structural parameters, are shown in Table 1.

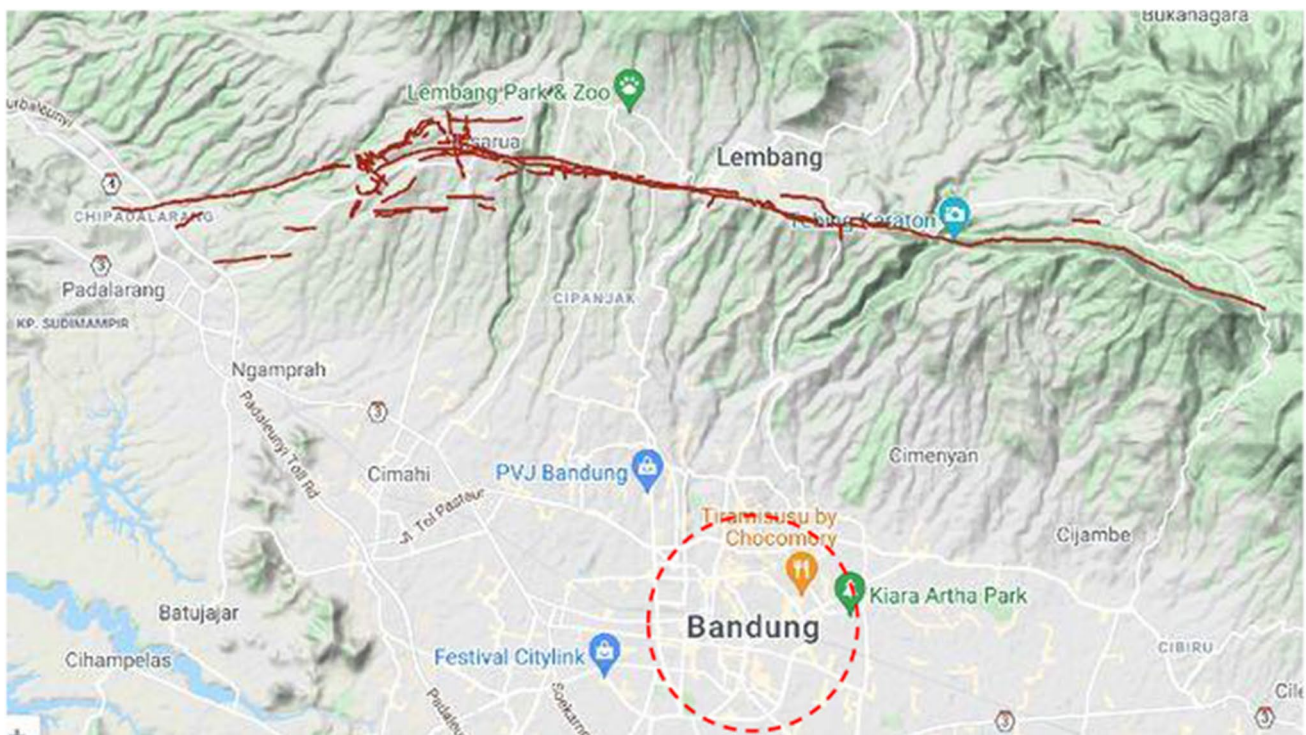


Fig. 1 Location of study

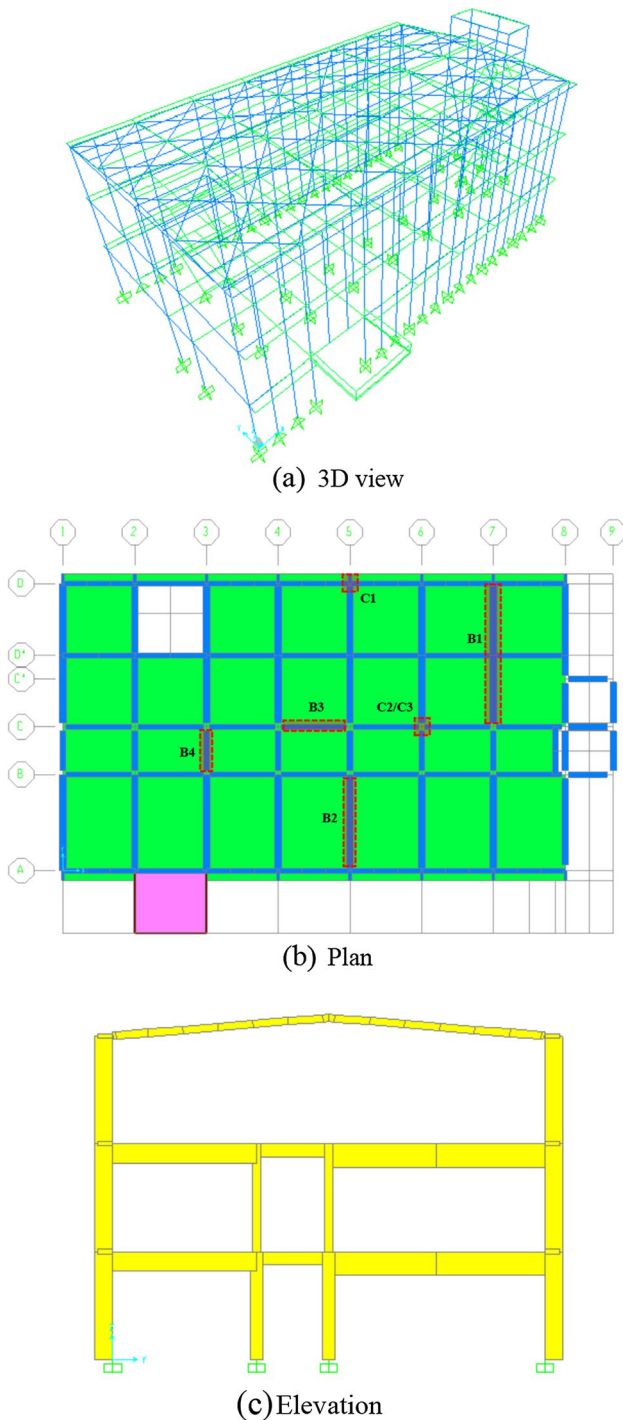


Fig. 2 Building configuration

2.2 Loading

The original structure was built in accordance with the 1971 edition of the Indonesian Reinforced Concrete Code (Peraturan Beton Bertulang Indonesia (Indonesian Concrete Reinforced Regulation), 1971) and the 1970 Indonesian Load Code (Peraturan Muatan Indonesia (Indonesia Load

Table 1 Detail of structures

Name	Size (mm)	Story no	Grid
Column C1	300×600	1–3	Grids A, D, and 9
Column C2	300×400	1	Grids B and C
Column C3	300×300	2–3	Grids B and C
Beam B1	350×800	2–3, roof	$L=7.2$ m (Grids 1–8)
Beam B2	350×650	2–3, roof	$L=4.8$ m (Grids 1–8)
Beam B3	250×550	2–3, roof	$L=3.6$ m (Grids A-D)
Beam B4	300×430	2–3, roof	$L=2.4$ m (Grids 1–9)
Rafter R	WF250×125x6×9	Rooftop	Grids 1–8
Plate P1	$t=200$	2–3	Office area, Stair landing
Plate P2	$t=300$	2–3	Laboratory area, Stair
Plate P3	$t=100$	Rooftop	Roof

Regulation), 1970) (Peraturan Muatan Indonesia (Indonesia Load Regulation), 1970). The design was modified for this study in accordance with the provisions of the most recent 2019 edition of Indonesian National Standard 1726 (Badan Standardisasi Nasional 2019) for seismic design and Indonesian National Standard 1727 (Badan Standardisasi Nasional 2020) for load specification. According to the 2019 edition of Indonesian National Standard 1726, the structure was designed as an Ordinary Moment Resisting Frame (OMRF) building for seismic loads ($R=3, \Omega_0=3, C_d=2.5$). For the seismic design of a building, the parameters R, Ω_0 and C_d represent the ductility-related factor, over-strength related factor, and lateral displacement magnification factor, respectively. The MCE_R response spectrum for Bandung was used to calculate the design base shear represents a 1.0% probability of collapse within 50 years.

Based on Fig. 3, design earthquake spectral response acceleration parameters at short periods, S_{DS} , and at 1 s periods, S_{D1} , shall be determined from Eqs. 1 and 2, respectively.

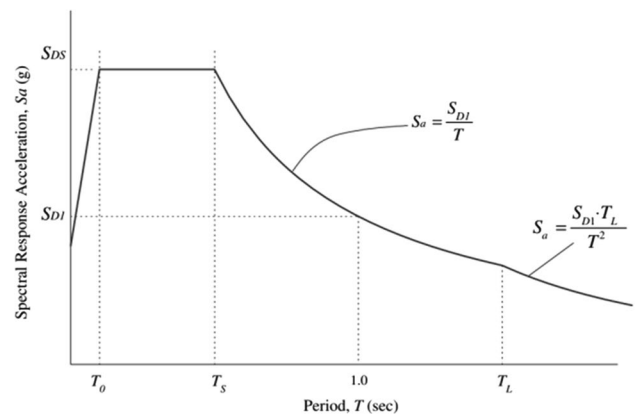


Fig. 3 Design Response Spectrum (ASCE/SEI 7-16, 2016)

$$S_{DS} = \frac{2}{3} S_{MS} \tag{1}$$

$$S_{D1} = \frac{2}{3} S_{M1} \tag{2}$$

Where S_{MS} = the MCER, 5% damped, spectral response acceleration parameter at short periods adjusted for site class effects. S_{M1} = the MCER, 5% damped, spectral response acceleration parameter at a period of 1 s adjusted for site class effects. S_{DS} = design, 5% damped, spectral response acceleration parameter at short periods. S_{D1} = design, 5% damped, spectral response acceleration parameter at a period of 1 s

As shown in Fig. 4, the foundation was assumed to be on soil represented by five site class (SA = hard rock, SBC = rock, SC = very dense soil and soft rock, SD = stiff soil and SE = soft soil).

The reinforced concrete office with laboratory research building had been modeled and analyzed using software for structural analysis and design. The loads that are considered in this analysis are gravity load (dead and live load), wind load, and seismic load. The structure was designed to withstand a superimposed dead load (SIDL) of 1.44 kN/m² at floors, 3.1 kN/m² for stairs, and 0.39 kN/m² at the roof, and 2.35 kN/m² for a brick wall, in addition to self-weight of the structural members, and a 2.4 kN/m² live load at the office area, 3.83 kN/m² at the corridor, 4.79 kN/m² at the staircase and laboratory area, and 0.96 kN/m² at the roof. For some office areas, live load is 0.72 kN/m² for partition. The wind load is applied at 0.77 kN/m² for closed or half-closed buildings and 0.38 kN/m² for roofs. There are several combinations of load cases that were applied to the building in this research based on the most recent 2019 edition of Indonesian

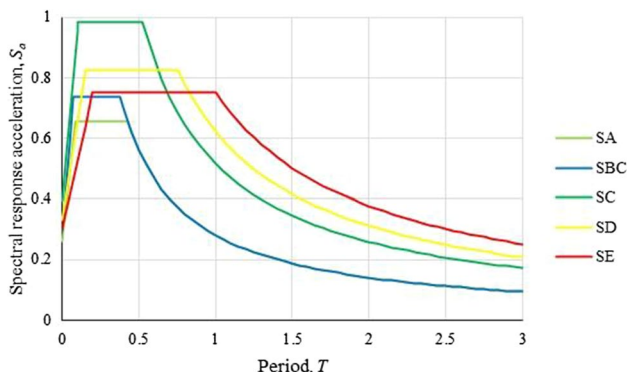


Fig. 4 Response spectrum (PuSGeN et al. 2021)

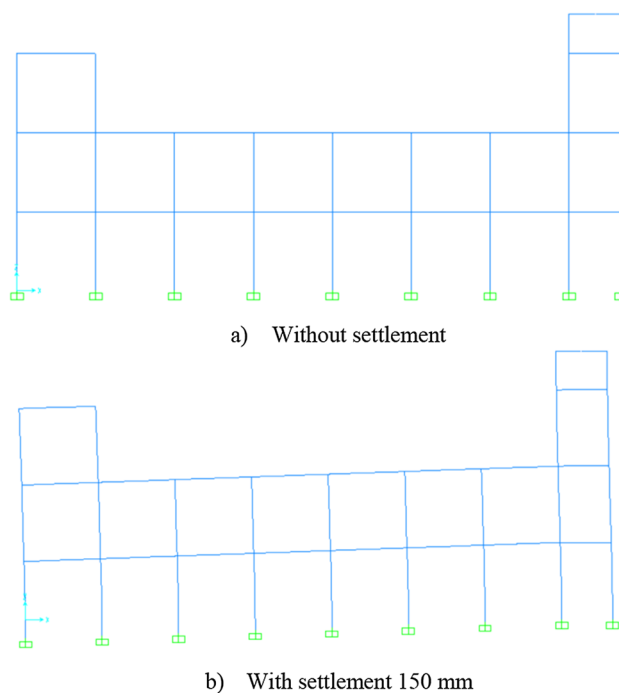


Fig. 5 Frame without and with foundation settlement

National Standard 1726 for seismic design. Fig. 5 shows a structure model without and with foundation settlement. The settlement is selected at 150 mm, which is in accordance with Indonesian National Standard 8460.

The key variable of all structure model is presented in Table 2. Structure models are labeled in two segments that are connected by hyphens. The label is led by description of soil type and followed by the depth of maximum settlement foundation.

Table 2 Structure model parameters

	Soil type	Settlement (mm)
SA_0	Hard rock	0
SBC_0	Rock	0
SC_0	Very dense soil and soft rock	0
SD_0	Stiff soil	0
SE_0	Soft soil	0
SA_150	Hard rock	150
SBC_150	Rock	150
SC_150	Very dense soil and soft rock	150
SD_150	Stiff soil	150
SE_150	Soft soil	150

3 Results and Discussion

The seismic base shear force that acts on the structure, lateral displacement, inter-story drift, and internal forces for RC structures are discussed and presented together with the factors that influence them.

3.1 Seismic Base Shear Force

The base shear is the total lateral force design at the base of the building. The base shear is calculated depending on the building's vibration period and the type of soil. The fundamental periods of the structures in *x*- and *y*-direction are 0.463s and 0.359s, respectively. Table 3 shows the spectral response acceleration and seismic base shear force that is acting on the model. It is observed that very dense soil and soft rock (SC) experienced the largest seismic base shear force, which is 454.06 tons in both directions. This result indicates that the magnitude of the base shear force does not depend on the type of soil.

Table 3 Sa and Base shear

	x-direction		y-direction	
	Sa (g)	Base shear (ton)	Sa (g)	Base shear (ton)
SA_0 and SA_150	0.607	279.85	0.655	302.71
SBC_0 and SBC_150	0.607	279.85	0.737	326.65
SC_0 and SC_150	0.983	454.06	0.983	454.06
SD_0 and SD_150	0.826	381.59	0.826	381.59
SE_0 and SE_150	0.751	346.95	0.751	346.95

3.2 Lateral Displacement

Lateral displacement is important when structures are subjected to lateral loads like seismic or wind loads. Lateral displacement is affected by structure height and slenderness because structures become more vulnerable to lateral load as building height increases. Figs. 6, 7, 8 and 9 show lateral displacement in four directions under different base shear forces (depending on soil type) and foundation settlement. All the structure models are analyzed in the software structure analysis with the configuration shown in Fig. 2 and Table 1.

It has been seen from Figs. 6a, 7, 8 and 9a that with the change in soil type (which consequently changes the base shear force) and without foundation settlement, the value of lateral displacement varies. The largest lateral displacement value is 57.14 mm on structure model SC_0 at *X*-direction positive. The displacement of site soil SC is the greatest among the other models. The top displacement in the *X* and *Y* directions for SC_0 is greater than 50 mm. The smallest lateral displacement value is 33.59 mm on structure model SA_0 at *Y*-direction positive.

The effect of foundation settlement makes the lateral displacement larger, especially in the *X*-direction. In the *X*-axis direction, the highest increase occurred in hard rock (SA), which was 130%, while the smallest increase occurred in rock soil type (SBC), which was 80%. On the *Y* axis, the displacement value only increases by about 3% to 6% in all types of soil conditions.

3.3 Inter-Story Drift

Inter-story drift is the drift of one level of a multi-story building relative to the level below as the building sways during an earthquake. The inter-story drift can not only measure the damage degree and performance level of the structure but also intuitively reflect the deformation between the layers and the

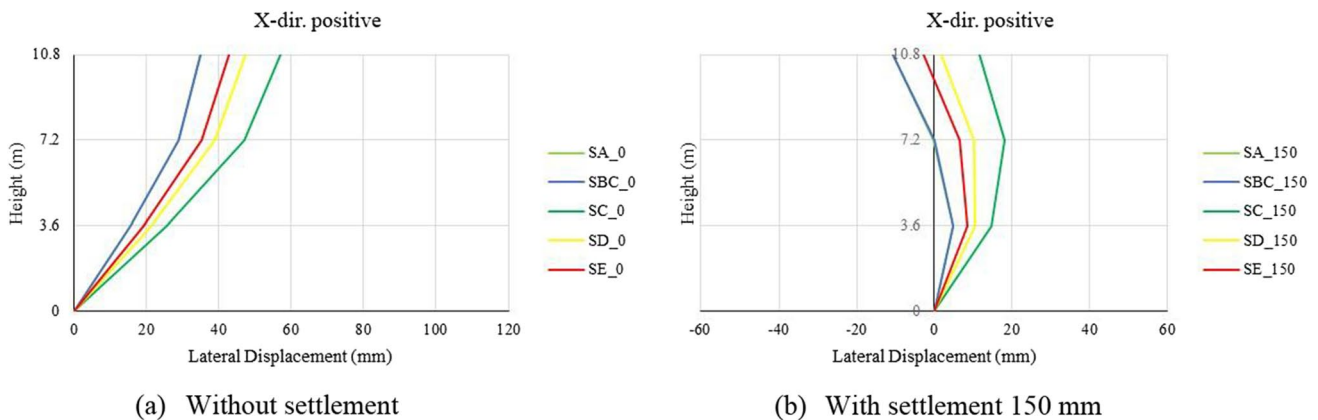


Fig. 6 Story displacement of static analysis along *X*-direction positive

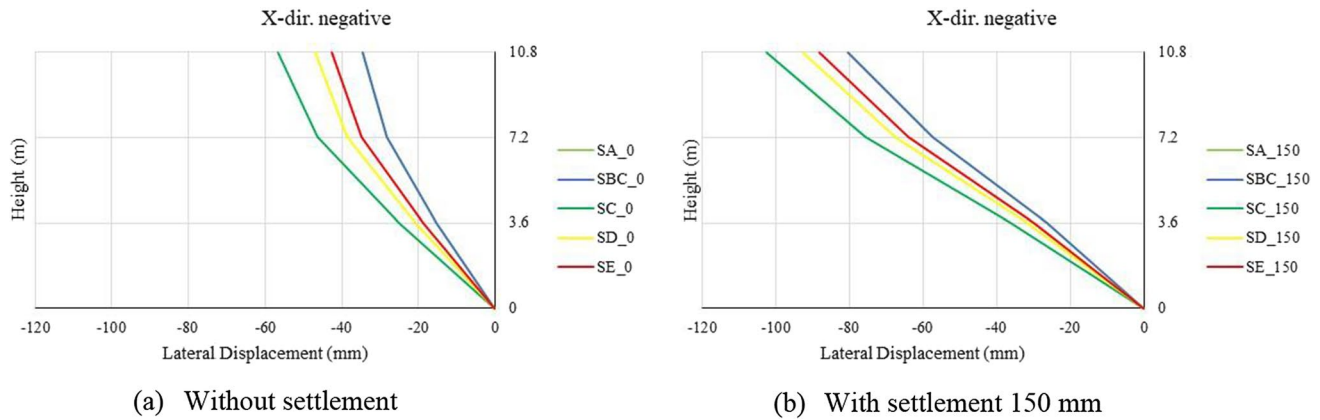


Fig. 7 Story displacement of static analysis along X-direction negative

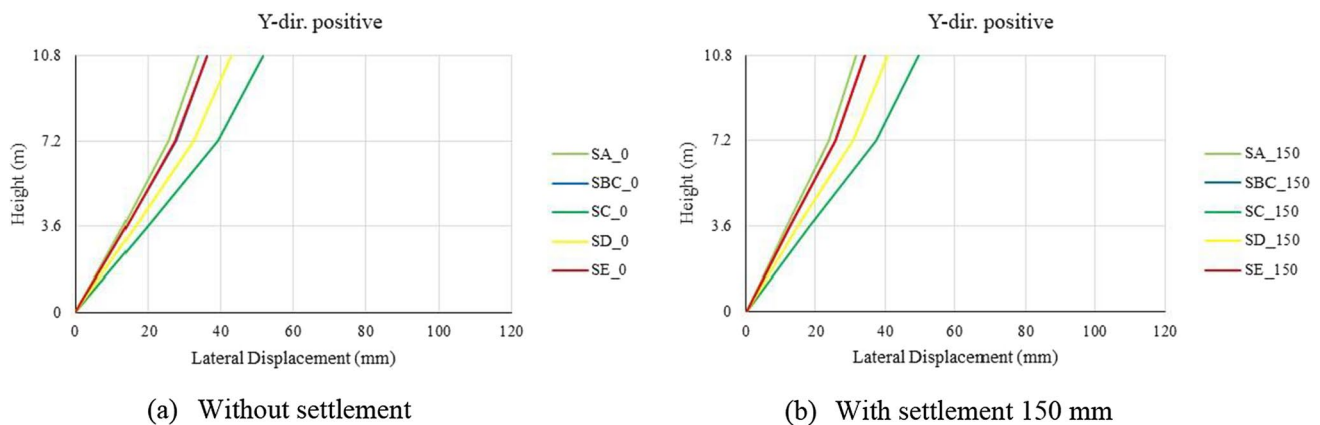


Fig. 8 Story displacement of static analysis along Y-direction positive

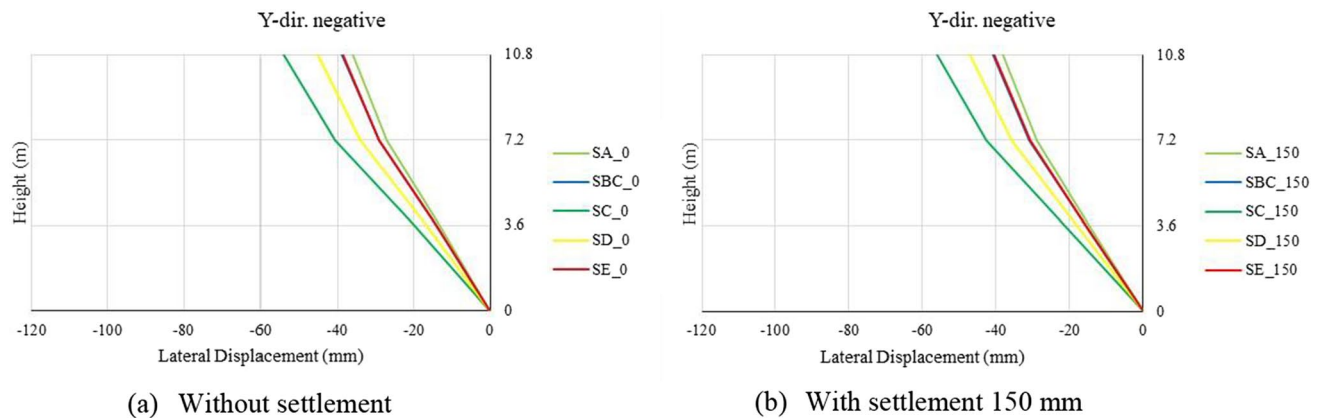


Fig. 9 Story displacement of static analysis along Y-direction negative

overall deformation of the structure. The maximum relative deformation between layers is used as the overall performance index of the structure, so that the overall performance index of the structure is obtained. Therefore, in this paper, when studying the response of a RC frame structure to different soil

types and foundation settlement, the maximum inter-story drift of the structure is selected as an index for determination. The limit value of interstory drift of a RC structure under seismic load is $0.02h_{sx}$, where h_{sx} is the story height. According to SNI

1726, the story drift in any story due to the minimum specified lateral load shall not exceed 72 mm.

To calculate inter-story drift based on Fig. 10 and Eq. 3, a three-story RC building under which five different soil types (hard rock, rock, very dense soil and soft rock, stiff soil and soft soil) is investigated.

The deflection at level x (δ_x) used to compute the design story drift, shall be determined in accordance with the following equation:

$$\delta_x = \frac{C_d \delta_{xe}}{I_e} \tag{3}$$

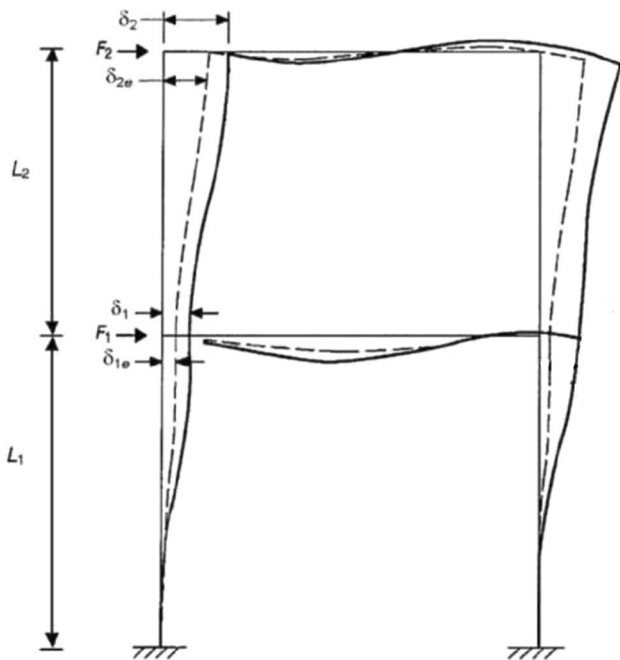


Fig. 10 Story Drift Determination (ASCE/SEI 7-16, 2016)

C_d = deflection amplification factor (2.5). δ_{xe} = deflection at the location required by this section determined by an elastic analysis. I_e = Importance Factor (1.0)

Figs. 11, 12, 13 and 14 show the values of the maximum inter-story drift of structures with different soil types and settlement foundations. In general, the maximum inter-story drift of the structure increases with settlement and is location dependent.

As shown in Fig. 12(b), due to settlement of 150 mm, the value of the maximum inter-story drift at the second and third floors exceeds the limit of the elastic inter-story drift of 72 mm. The SC, SD, and SE soil types and inter-story drift on the 2nd and 3rd floors exceeded the permit limit, while the SA and SB soil types only on the 3rd floor exceeded the permit limit.

The effect of foundation settlement makes δ the inter-story drift larger, especially in the X-axis direction. The highest increase occurred in hard rock (SA), which was 270%, while the smallest increase occurred in medium rock (SC), which was 160%.

On the Y axis, the increase in value of inter-story drift is less than 2% in all types of soil conditions. Figs. 13 and 14 show the value of maximum inter-story drift along Y axis. This shows that even if a 150 mm settlement occurs, the maximum inter-story drift ratios do not exceed the limit.

3.4 Bending Moment and Shear Force

The shear force and bending moment results for ten structure models have been taken from the analysis results, which are tabulated below. The bending moment and shear force are calculated for each load combination and seismic zone.

Bending moment and shear values in columns and beams are shown in Tables 4, 5, 6, 7, 8, 9 and 10. For column structures C1, C2, and C3 as well as beams B1 and B2, there was no significant increase in bending moments and shear forces between before and after foundation settlement. Column

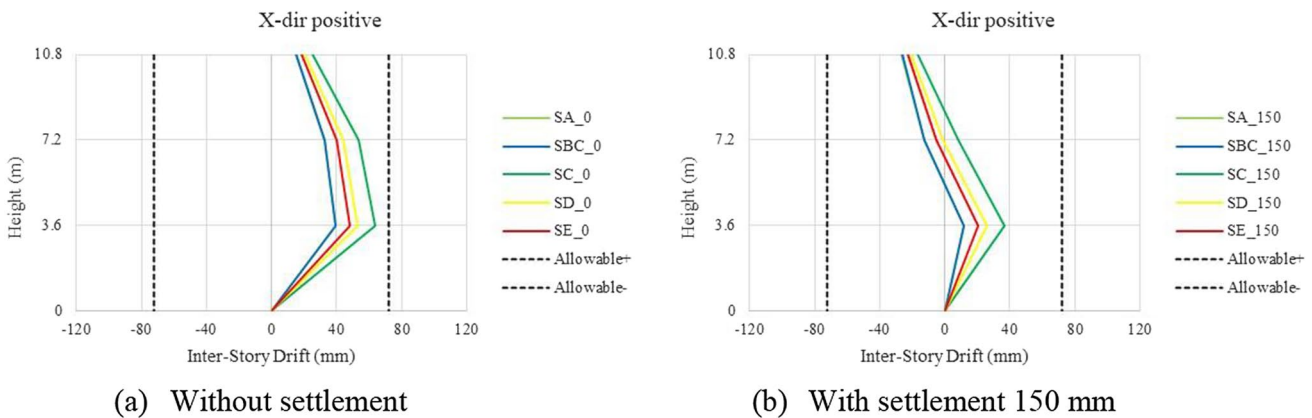


Fig. 11 Inter-story drift along X-direction positive

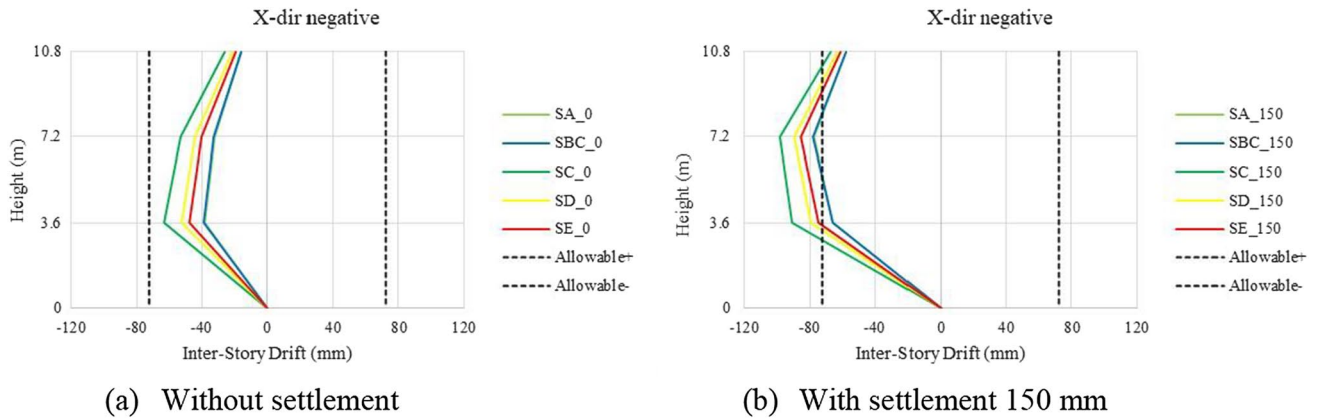


Fig. 12 Inter-story drift along X-direction negative

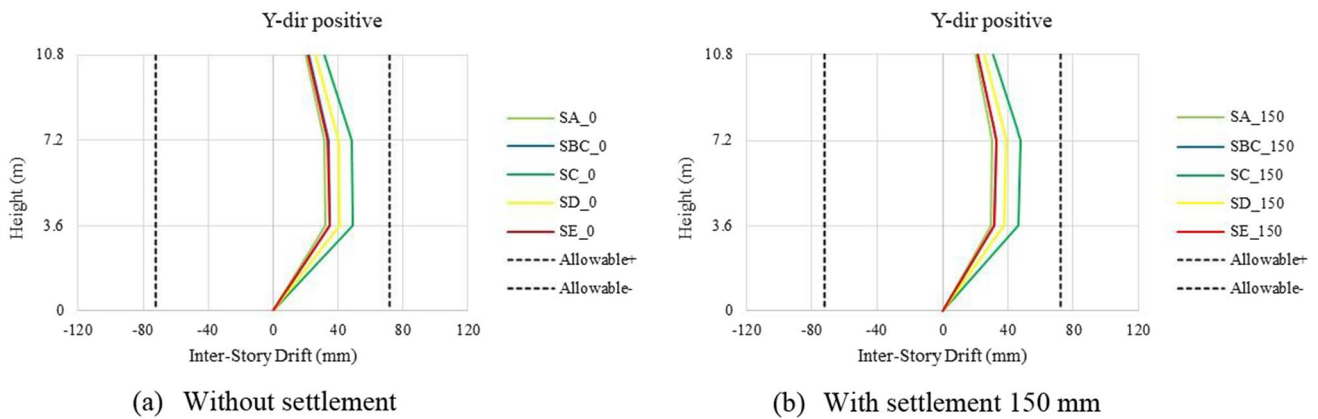


Fig. 13 Inter-story drift along Y-direction positive

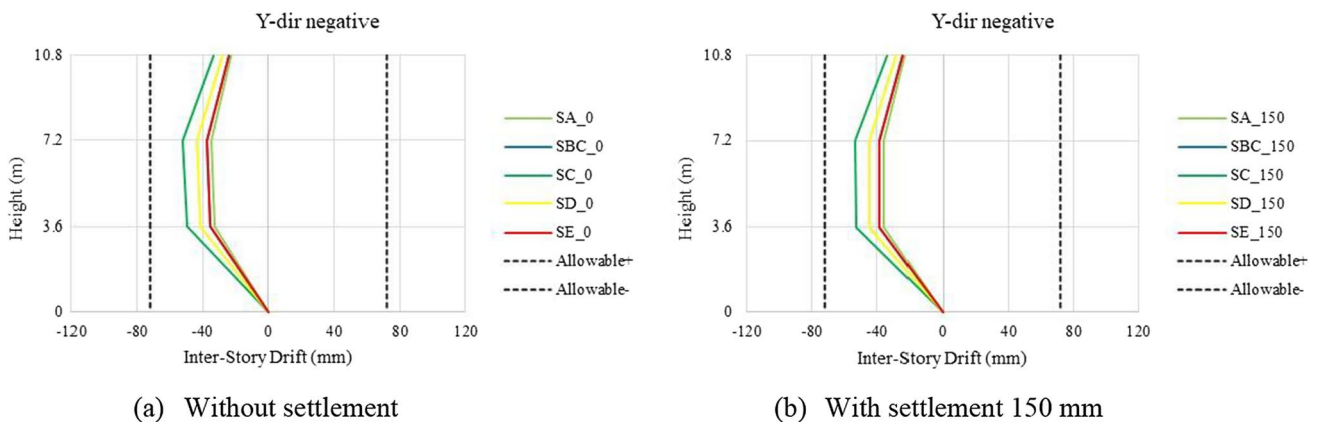


Fig. 14 Inter-story drift along Y-direction negative

C1 has a change of less than 1.5%, both an increase and a decrease in the value of the moment, while for the shear force there was an increase of approximately 3.0% to 4.5% for all soil types. In column C2, the moment changes from 6.0 to 9.5%, while the shear force increases from 15 to 25%.

For column C3, the increase in moment and shear due to foundation settlement is 1.85–2.71%. The rock soil conditions experienced a maximum increase and decrease in the moment and shear values in the C1, C2, and C3 columns.

Table 4 Comparison maximum bending moment and shear force for column C1

Element	C1 600×300			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	52.49	275.13	51.87	287.53
SBC	55.84	295.78	55.48	308.18
SC	76.24	415.34	76.82	427.78
SD	64.62	346.46	64.57	358.86
SE	55.89	294.32	55.33	306.72

Table 5 Comparison maximum bending moment and shear force for column C2

Element	C2 400×300			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	17.34	14.82	18.95	18.53
SBC	18.61	14.85	20.22	18.56
SC	26.04	23.69	27.65	27.43
SD	21.76	19.78	23.38	23.49
SE	18.53	18.04	20.15	21.74

Table 6 Comparison maximum bending moment and shear force for column C3

Element	C3 300×300			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	8.11	4.46	8.33	4.58
SBC	8.66	4.76	8.88	4.88
SC	11.79	6.49	12.02	6.61
SD	9.98	5.49	10.21	5.61
SE	8.60	4.73	8.83	4.85

As a result of the decrease, beam B1 experienced an increase in the value of the moment by 16 to 24% for the

Table 7 Comparison maximum bending moment and shear force for beam B1

Element	B1 350×800			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	37.29	36.88	46.16	39.98
SBC	39.06	38.39	46.35	40.69
SC	51.69	48.68	60.45	49.81
SD	44.74	42.96	54.14	45.44
SE	41.29	38.84	51.20	43.32

Table 8 Comparison maximum bending moment and shear force for beam B2

Element	B2 350×650			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	27.45	17.66	28.96	18.35
SBC	29.08	18.51	30.60	19.19
SC	38.63	23.41	40.15	24.09
SD	33.14	20.59	34.65	21.27
SE	28.99	18.46	30.51	19.14

Table 9 Comparison maximum bending moment and shear force for beam B3

Element	B3 250×550			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	20.08	34.82	28.08	55.76
SBC	20.27	36.49	28.27	57.79
SC	31.75	48.08	39.65	68.69
SD	26.56	41.67	34.55	62.30
SE	24.07	37.10	32.07	57.49

Table 10 Comparison maximum bending moment and shear force for beam B4

Element	B4 300×430			
	Without settlement		With settlement 150 mm	
	Moment (t-m)	Shear (t)	Moment (t-m)	Shear (t)
SA	10.32	12.49	23.98	25.24
SBC	10.32	12.68	23.98	25.25
SC	16.65	19.67	29.53	31.35
SD	13.87	16.45	27.08	28.65
SE	12.63	14.86	25.99	27.46

moment, and 2.3 to 11.5% for the shear force. The smallest increase value occurred in SC soil conditions, while the largest increase occurred in SE soil conditions.

The increase in the moment and shear values in Beam B2 is not too large, around 3.9–5.5% for the moment and 2.9–3.91% for the shear. SC soil conditions have the smallest increase in percentage value, while SA soil conditions have the largest increase.

Significant value changes occurred in beams B3 and B4 whose values increased by more than 50%. The moment value in beam B3 increased by 24–39.84%, while the shear value increased by approximately 42–60.14%. SC soil conditions experienced the lowest increase, while SA soil conditions experienced the largest increase. According to

Figure 2, the maximum shear force and moment bending beam B3 occur at 2nd floor grid B7-8 and stair landing grid D2-3, respectively. For structures with foundation settlement, maximum, shear force and moment bending beam B3 happen at 2nd floor grid C7-8 and stair landing grid D2-3, respectively.

Figure 2 depicts shear force and moment bending beam B4 without foundation settlement at stair landing grids 9B-C and D'8-'9. Maximum shear force and moment bending beam B4 occur at 2nd floor grid D'8-9 for foundation settlement structures.

4 Conclusions

In this paper, the effect of different soil types and foundation settlement on the structure's performance is studied by comparing the maximum lateral displacement, inter-story drift, and internal forces under seismic load. The following are the main findings and conclusions of this research:

- (1) Even though it is an old building, if there is no foundation settlement, the inter-story drift is still within allowable limits;
- (2) The inter-story drift value exceeds the permit limit due to foundation settlement;
- (3) SC (very dense soil and soft rock) soil type results in the largest values of base shear, displacement, inter-story drift, and internal force;
- (4) The hard rock soil type SA produces the largest increase in internal forces when the structure has a foundation settlement.

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Author Contributions LSBW: Analysis and/or interpretation of data, Conceptual, Writing—Original Draft. MHP: Data Acquisition, Writing—Review & Editing. HAF: Data Acquisition, Analysis and/or interpretation of data. SS: Review & Editing. AA: Data Acquisition, Analysis and/or interpretation of data. MP: Review & Editing.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest or competing interests that could have appeared to influence the work reported in this paper.

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