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EVALUATION OF AN RC FRAME BUILDING EXPOSED TO DIFFERENTIAL SETTLEMENT IN PADANG CITY, INDONESIA

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ABSTRACT: Buildings are essential infrastructures in everyday life, so their structure must be carefully planned to reduce the potential for damage. One of the damages that can occur to buildings is differential settlement, as in the case of a Reinforced Concrete (RC) frame building exposed to differential settlement in an office building in Padang City, West Sumatra, Indonesia. The building was built in 2011 using the old Indonesian seismic building code. Therefore, it is necessary to conduct a building structure assessment to determine its feasibility and safety based on current Indonesian building standards. The building structure assessment involves the evaluation of the existing building, analysis of the geometry of the building, and structural analysis of the existing building using the finite element method (ETABS v21) computer program. The results of the study show that the building's differential settlement is 1.85%, exceeding the allowable limit of 1/300. The load effect due to differential settlement results in an increase in internal forces in the beam, such as moment and shear capacity of around 16%, while the internal forces in the column experience a decrease in the maximum axial force of 89%. Due to the additional load of the differential settlement, almost all capacity of existing structural elements, such as columns and beams, is reduced so that they do not meet current building codes. Consequently, it is recommended that the building not be used or repurposed for other activities and that it be demolished instead.

Keywords: Building Damage, Differential Settlement, Geometric, Moment Capacity, Shear Capacity.

1. INTRODUCTION

Buildings are essential infrastructures in everyday life, so their structure must be carefully planned to reduce the potential for damage. Some things that can cause damage to buildings include building age, planning errors, and earthquakes [1]. One of the damages that can occur in buildings is differential settlement.

Differential settlement poses a direct threat to the integrity and capacity of a structure. This differential settlement could result from many activities, including changes in moisture content, vibration, liquefaction, and nearby construction activities. The differential settlement usually results in a settlement pattern that impacts the building structure through various damages, ranging from cracks to structural failure, that can compromise the integrity of structural safety and long-term sustainability [2].

Recently, many methodologies have been conducted to determine the differential settlement of the building, such as experimental investigation on the structural response of multi-story buildings subjected to differential settlement of its foundations [3], response of multi-story steel structure subjected to differential settlements of its foundation [4], Fragility curves for different classes of existing RC buildings underground differential settlements [5], structural response of RC frame under surface curvature and differential settlement in mining areas [6].

Fig. 1 The RC frame building exposed to differential settlement in Padang City, West Sumatra, Indonesia

One of the damages that can occur to buildings is differential settlement, such as in the case of Reinforced Concrete (RC) frame building exposed to differential settlement in an office building in Padang City, West Sumatra, Indonesia. The building was built in 2011 using the old Indonesian seismic building code (SNI 1726:2002) and Reinforced Concrete (RC) (SNI 2847:2002), as shown in Fig. 1. The building design follows the old Indonesian building code; however, it has experienced differential settlement until now. Therefore, it is necessary to conduct a building structure assessment to determine its feasibility and safety based on current

Indonesian building standards.

This study focuses on the analysis of structural responses to differential settlements of the existing building to earthquake loads according to the current Indonesian seismic code.

2. RESEARCH SIGNIFICANCE

This study develops an evaluation of the building structure that discusses the differential settlement, which results in reduced stability of the building. The effect of additional loads due to differential settlement is also discussed in this paper. The results of this study help engineers determine the appropriate method for handling buildings that experience differential settlement. In addition, to ensure building safety, damaged areas and resulting impacts were identified, which are of concern in this study, such as damage to structural elements and building levelling due to differential settlement.

3. EVALUATION OF EXISTING BUILDING

3.1 Visual Assessment

Visual assessment includes checking for damage to structural elements, evaluating the condition of existing building geometry, and assessing the quality of existing building materials.

Fig. 2 The right side of the building is lifted

Fig. 3 The left side of the building has decreased

Fig. 4 Damage to structural elements

Based on visual observations, the right side of the existing building was uplifted around 46 cm from ground level, as shown in Fig. 2, while the left side of the building has decreased around 48 cm (Fig. 3). Additionally, there are cracks in the beams on the 1st floors, as shown in Fig. 4. This differential decline continues to occur every year.

3.2 Collecting Geometric Measurement Data

The aim of collecting building geometric data is to determine the building leveling using theodolite measuring equipment. Figs. 5 and 6 illustrate the geometric measurements that have been conducted. The results of these measurements allow for the description of the flatness (contour) of the measured building.

Fig. 5 Geometric measurements on the outside of the building

Fig. 6 Geometric measurements on the roof top of the building

3.3 Collecting Concrete Quality Data

Table 1 Concrete quality

Structural Element	Column	Beam	Plate
Punch angle	0°	0°	90°
Code	2	13	14
As building	F1	B3	A-B
Corrected compressive strength (N/mm^2)	28.78	41.24	24.78

Table 1 shows that the minimum concrete quality value of the structural element is 24.78 MPa. This value will be used as input in the structural analysis of the existing building [7].

4. GEOMETRIC ANALYSIS OF BUILDING

4.1 Geometric Measurement of Building

Geometric measurements are carried out on the 1st floor and the roof floor of the building. The measurement results show the flatness contour of the building on both the 1st floor and the roof floor. Based on the measurements, the front right side was uplifted by +46 cm, while the rear left side experienced a settlement of -48 cm. The flatness contour on the 1st floor and the roof floor is illustrated in Figs. 7 and 8.

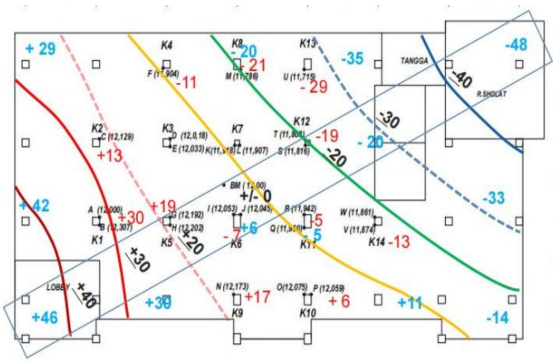

Fig. 7 Flatness contour on the 1st floor

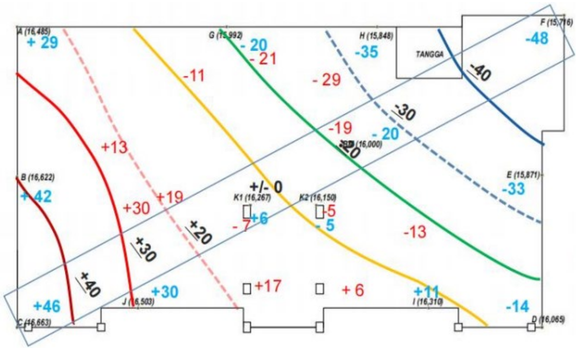

Fig. 8 Flatness contour on the roof floor

The pattern of building decline consistently persists compared to monitoring results from previous years. The maximum elevation difference between the front right side and the rear left side of the building is approximately 94 cm.

4.2 Building Settlement

Based on the measurement results, it can be observed that the building has experienced a significant slope. When the maximum slope is calculated based on the diagonals of the highest and lowest elevations, the value of the differential settlement is:

$$\delta = \frac{-(-48-46)}{\sqrt{45^2+23.4^2}} = \frac{94}{50.72} = 1.85\%$$

The value is calculated as (5.6)/(300) or (2.8)/(150). When compared with the requirements to ensure building safety, specifically outlined in SNI 8460:2017 article 9.2.4.3 [8], the permissible differential settlement for a building is 1/300. Based on this result, the existing building's settlement is nearly six times greater than the allowed limit, indicating a critical condition where structural collapse could occur.

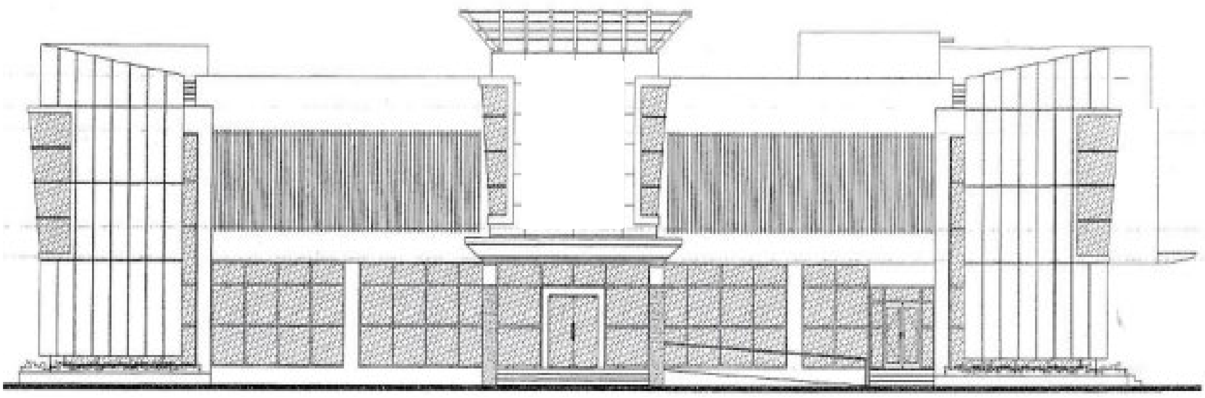

Fig. 9 The front view of existing building

5. STRUCTURAL ANALYSIS

5.1 Building Description Data

Building description data, such as concrete quality, reinforcing steel quality, dimensions of structural elements, and room function, were obtained from as-built drawings. Table 2 describes the buildings parameter in this study.

The Indonesian building standards used in the analysis of existing building structures refer to current Indonesian building codes: SNI 1726:2019 for seismic code [9], SNI 2847:2019 for RC Structure code [10], SNI 1727:2020 for minimum loads code [11], and SNI 8360 2017 for Geotechnical Design Requirements [8]. The building has main columns and beams with reinforcement bars, as illustrated in Tables 3 and 4. The front view of the existing building can be seen in Fig. 9.

Table 2 Building description

Parameter	Building Description
Building type	Office building
Building location	Teluk Bayur, Padang
Number of floors	2 Floors
Building width	21 m
Building length	42 m
Concrete quality	24.78 MPa
Steel grade	350 MPa

Table 3 Details of column structural elements

No.	Type	Section (mm)		Flex. Reinf. Bar	Shear Reinf. Bar	
		Depth	Width		Support	Mid-span
1	K1	600	600	16D19	4Ø10-115	4Ø10-150
2	K2	800	600	20D19	4Ø10-115	4Ø10-150

Table 4 Details of beam structural elements

No.	Type	Section (mm)		Support Area		Midspan Area	
		Depth	Width	Tensile	Compr.	Tensile	Compr.
1	TB1	500	250	5D19	4D19	5D19	4D19
2	TB2	600	300	6D19	5D19	6D19	5D19
3	TB3	450	250	3D16	3D16	3D16	3D16
4	TB4	300	200	2D16	2D16	2D16	2D16
5	B1	515	250	6D19	4D19	6D19	4D19
6	B1’	515	250	5D19	3D19	5D19	3D19
7	B2	450	250	5D19	3D19	5D19	3D19
8	B3	315	150	2D16	2D16	2D16	2D16
9	B4	250	150	2D13	2D13	2D13	2D13
10	B5	915	450	10D19	7D19	10D19	7D19

5.2 Structural Modeling

Structural modeling is performed using the finite element method with the ETABS v21 computer program to determine the internal forces within the structure [12]. The building model is depicted in Fig. 10.

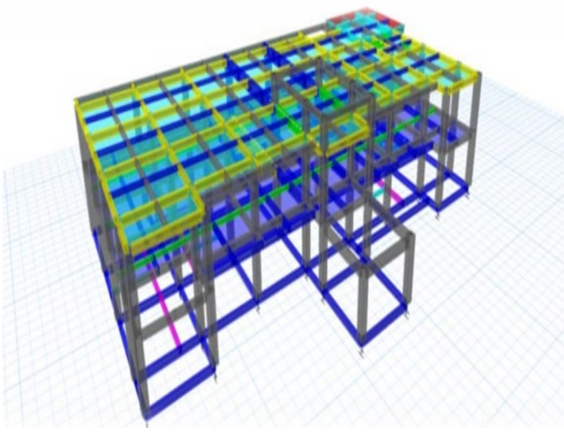

Fig. 10 3D Structural modeling of the building

5.3 Load Analysis

5.3.1 Vertical load

Vertical loads are categorized as gravity loads, which include dead and live loads. Dead loads are further classified into structural self-weight (DL) and additional dead loads (SIDL). The structure's self-weight is detailed in Table 5. In addition to the self-weight, dead loads also include additional dead loads, as illustrated in Table 6. Furthermore, the live load on the building is assumed to be 250 kg/m².

Table 5 Self weight of the building structure

Material load	Value (kg/m^2)
Slab cover 1 cm thickness	48
Slab mortar 2 cm thickness	42
Ceiling weight	20
Floor slab	110

Table 6 Additional dead load

Material load	Value (kg/m^2)
Slab mortar 2 cm thickness	42
Ceiling weight	20
Rainwater weight	50
Concrete roof	112

5.3.2 Horizontal load

One type of horizontal or lateral load is the force exerted by an earthquake. The structural analysis of the building employs an earthquake analysis approach using various dynamic response spectra. Analyzing the diverse response spectra is a method used to determine the dynamic response of a 3-dimensional building structure to the impact of an earthquake. This analysis method is known as the analysis of the variety of response spectra. The spectral response data for Padang City is presented in Table 7.

Table 7 Response Spectrum Data

Variabel	Value (g)
Ss	1.470921
S1	0.60
Fa	0.811632
Fv	2.00
SMs	1.193846
SM1	1.20
SDs	0.795897
SD1	0.80

Table 7 provides information for obtaining the response spectrum for earthquake design, as illustrated in Fig. 11.

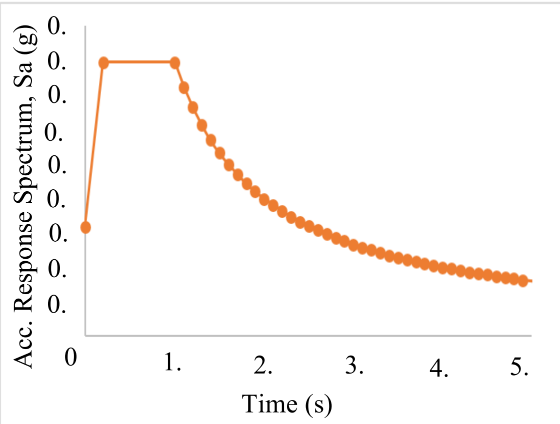

Fig. 11 Spectrum response of Padang City, Indonesia

5.3.3 Load due to differential settlement

The building experienced a differential settlement in certain parts, with a ground displacement of -48 cm. The differential settlement load was also input into ETABS v21, considering ground displacement on joint loads, as depicted in Fig. 12.

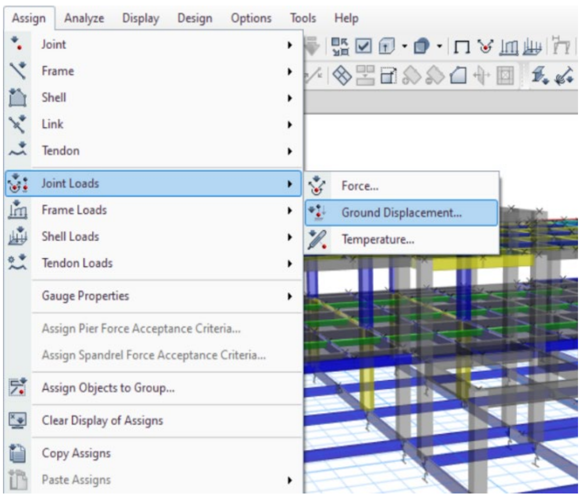

Fig. 12 Assign load due to differential settlement

5.3.4 Load combination

The loading combination takes into account the combinations and influences of seismic loads, as stipulated in SNI 1726:2019 [9]. Thus, the load combinations used are as follows:

1. 1.4 D
2. 1.2 D + 1.6 L
3. 1.4 D + L + 1.3 Ex + 0.39 Ey
4. 1.4 D + L + 1.3 Ex – 0.39 Ey
5. 1.4 D + L – 1.3 Ex – 0.39 Ey
6. 1.4 D + L – 1.3 Ex + 0.39 Ey
7. 1.4 D + L + 0.39 Ex + 1.3 Ey
8. 1.4 D + L – 0.39 Ex + 1.3 Ey
9. 1.4 D + L + 0.39 Ex – 1.3 Ey
10. 1.4 D + L – 0.39 Ex – 1.3 Ey
11. 0.7 D + 1.3 Ex + 0.39 Ey
12. 0.7 D + 1.3 Ex – 0.39 Ey
13. 0.7 D – 1.3 Ex – 0.39 Ey
14. 0.7 D – 1.3 Ex + 0.39 Ey
15. 0.7 D + 0.39 Ex + 1.3 Ey
16. 0.7 D – 0.39 Ex + 1.3 Ey
17. 0.7 D + 0.39 Ex – 1.3 Ey
18. 0.7 D – 0.39 Ex – 1.3 Ey

Where D is the dead load, L is the live load, Ex is the earthquake load in the x-direction, and Ey is the earthquake load in the y-direction.

5.4 Results and Discussion

Structural analysis is conducted on the entire building structure to ensure it is in alignment with the planning and existing conditions of the structure. This analysis is performed to investigate the current state of the building structure and its capacity to withstand loads in accordance with the current Indonesian building codes.

5.4.1 Column capacity

The building structure consists of the same column type on each floor, namely square columns measuring 60 cm x 60 cm with 16D19 flexural reinforcement bars. Based on the results of the structural analysis, a P-M interaction diagram can be drawn, as illustrated in Fig. 13.

Figs. 13 and 14 illustrate the P-M interaction diagram with and without load due to differential settlement of the column's axial-moment force points outside the P-M interaction diagram, indicating that the column structure element is not safe (not strong) in resisting the maximum working load combination.

Table 8 presents a comparison of the shear strength capacity of existing buildings with the maximum shear load acting on the columns. Based on the table, the column is unable to resist the shear load acting on the structure.

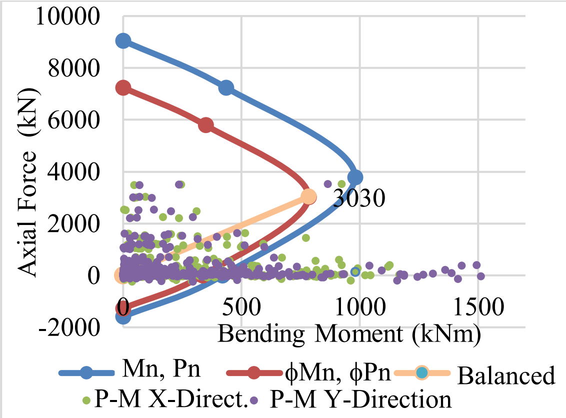

Fig. 13 Column P-M interaction diagram with load due to differential settlement

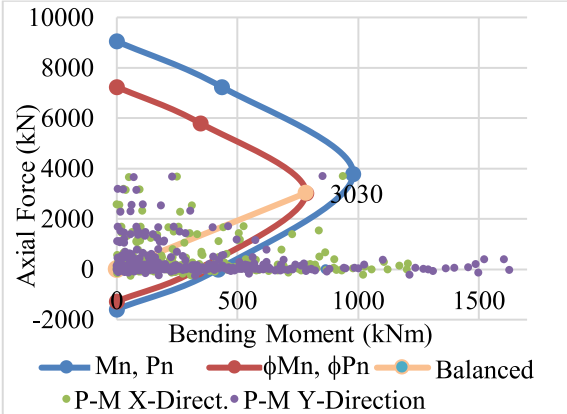

Fig. 14 Column P-M interaction diagram without load due to differential settlement

Table 8 Shear capacity of column

Ground Displacement	Dimension (mm)		Longitudinal rebar	Concrete Quality	Steel Grade (fy)	Vu (kN)	Shear Rebar	ϕVn (kN)	ϕVn ≥ Vu
	W	H							
With	600	600	16 D-19	247.8	350	712.41	4D10 – 115	428.35	NOT OK
Without	600	600	16 D-19	247.8	350	766.23	4D10 – 115	428.35	NOT OK

5.4.2 Beam capacity

Tables 9 and 10 detail the moment and shear capacity acting on each beam of the building structure. Table 9 displays the flexural capacity of the beam cross-section, while Table 10 presents the shear capacity of the beam cross-section. The calculation results for beam capacity indicate that all types of beams fail to resist the working load. It suggests that the beam capacity is insufficient to bear the load acting on the structure in accordance with the current Indonesian building codes.

Table 9 Moment capacity of beam

Beam/ Sloof Code	Dimension (mm)		Mu (kN.m)	Concrete Quality (K)	Steel Grade (Fy)	Rebar			ϕMn (kN.m)	ϕMn ≥ Mu
	W	H				Tensile	Comp.	Total Area (mm^2)		
TB12550	250	500	1473.953	248	350	5D-19	4D-19	2550.465	159.69	NOT OK
TB3245	250	450	469.340	248	350	3D-16	3D-16	1205.740	62.20	NOT OK
TB42030	200	300	101.906	248	350	2D-16	2D-16	803.639	25.42	NOT OK
2B12550	250	500	1416.564	248	350	6D-19	4D-19	2883.850	190.26	NOT OK
2B22545	250	450	376.773	248	350	5D-19	3D-19	2267.080	139.90	NOT OK
2B31530	150	300	97.923	248	350	2D-16	2D-16	803.639	24.64	NOT OK
2B41525	150	250	29.106	248	350	2D-13	2D-13	530.527	15.07	NOT OK
2B54590	450	900	3226.215	248	350	10D-19	7D-19	4817.545	629.38	NOT OK
2B64060	400	600	558.336	248	350	5D-19	3D-19	2267.080	201.41	NOT OK
2B73060	300	600	2523.819	248	350	8D-19	4D-19	3400.620	313.87	NOT OK
2B82560	250	600	446.718	248	350	5D-19	3D-19	2125.388	198.00	NOT OK
2B102575	250	750	440.685	248	350	5D-19	5D-19	2833.567	257.13	NOT OK
3B12550	250	500	1296.882	248	350	6D-19	4D-19	2833.850	190.26	NOT OK
3B22545	250	450	357.751	248	350	5D-19	3D-19	2267.080	139.90	NOT OK
3B31530	150	300	93.882	248	350	2D-16	2D-16	803.639	24.64	NOT OK
3B41525	150	250	14.156	248	350	2D-13	2D-13	530.527	13.40	NOT OK
3B54590	450	900	2616.719	248	350	10D-19	7D-19	4817.545	629.38	NOT OK
3B64060	400	600	587.236	248	350	5D-19	3D-19	2267.080	201.41	NOT OK
3B73060	300	600	2183.706	248	350	8D-19	4D-19	3400.620	313.87	NOT OK
3B82560	250	600	402.181	248	350	3D-19	3D-19	2125.388	198.00	NOT OK

Table 10 Shear capacity of beam

Beam/ Sloof Code	Dimension (mm)		Vu-Support (kN)	Vu-Midspan (kN)	Span (m)	Shear Rebar (kN)					
	W	H				Support	ϕVn (kN)	ϕVn ≥ Vu-S	Midspan	ϕVn (kN)	ϕVn ≥ Vu-M
TB12550	250	500	577.56	481.30	6	D10-23	490.93	NOT OK	D10-150	117.61	NOT OK
TB3245	250	450	176.80	147.33	6	D10-82	153.22	NOT OK	D10-150	104.54	NOT OK
TB42030	200	300	94.09	78.40	6	D10-87	86.24	NOT OK	D10-150	59.66	NOT OK
2B12550	250	500	642.11	535.10	6	D10-20	545.80	NOT OK	D10-150	117.61	NOT OK
2B22545	250	450	157.25	131.04	6	D10-98	136.29	NOT OK	D10-150	104.54	NOT OK
2B31530	150	300	66.07	55.06	6	D10-100	72.47	OK	D10-150	53.98	NOT OK
2B41525	150	250	41.13	34.28	6	D10-100	57.98	OK	D10-150	43.19	OK
2B54590	450	900	898.52	748.77	6	D10-40	643.94	NOT OK	D10-150	299.32	NOT OK
2B64060	400	600	278.22	231.85	6	D10-96	227.21	NOT OK	D10-150	181.20	NOT OK
2B73060	300	600	1055.3	879.37	6	D10-16	861.78	NOT OK	D10-150	156.22	NOT OK
2B82560	250	600	168 .76	140.64	6	D10-100	184.41	OK	D10-150	143.75	NOT OK
2B12575	250	750	168.20	140.17	6	D10-100	233.71	OK	D10-150	182.95	NOT OK
3B12550	250	500	552.56	460.46	6	D10-24	469.67	NOT OK	D10-150	117.61	NOT OK
3B22545	250	450	248.91	207.42	6	D10-52	215.72	NOT OK	D10-150	104.54	NOT OK
3B31530	150	300	52.73	43.94	6	D10-100	72.47	OK	D10-150	53.98	OK
3B41525	150	250	13.96	11.55	6	D10-100	57.98	OK	D10-150	43.19	OK
3B54590	450	900	761.59	634.66	6	D10-51	545.81	NOT OK	D10-150	299.32	NOT OK
3B64060	400	600	281.68	234.73	6	D10-94	230.03	NOT OK	D10-150	181.20	NOT OK
3B73060	300	600	898.86	749.05	6	D10-19	734.07	NOT OK	D10-150	156.22	NOT OK
3B82560	250	600	140.59	117.16	4	D10-100	184.41	OK	D10-150	143.75	OK

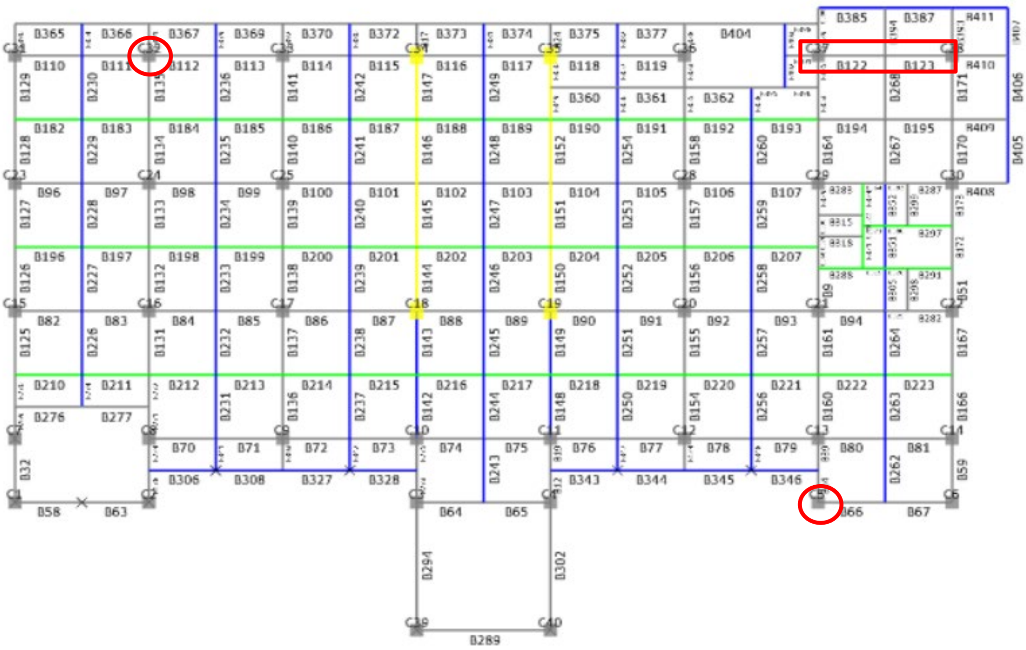

Fig. 15 Location of maximum internal forces in structural elements due to differential settlement loads

Table 11 Percentage of comparison internal forces with and without load due to differential settlement on beam

Floor	Code	Moment (kNm)		Percentage (%)	Shear (kN)		Percentage (%)
		Without	With		Without	With	
1	B31	240.85	279.13	13.71	123.08	135.99	9.49
2	B123	382.83	454.68	15.80	137.15	161.60	15.13
3	B123	359.34	421.26	14.70	114.65	136.35	15.92

5.4.3 Effect of loads due to differential settlement

The location of the maximum internal force in the structural element due to differential settlement is also reviewed to assess its impact on the structural element (Fig. 15). Table 11 illustrates the comparison of the maximum internal forces in the beams on each floor with and without the loads due to differential settlement. Overall, all beam structural elements experience an increase in internal force due to the influence of differential settlement loads.

Table 12 The effect of loads due to differential settlement on column structural elements

Floor	Code	Axial Force (kN)		Perc. (%)
		Without	With	
1	C5	4.87	20.35	76.07
2	C32	7.01	67.82	89.66

In terms of increasing internal force, the moment force on the beam experienced a significant rise, with a maximum percentage increase of 15.8%. Meanwhile, the shear force on the beam saw a maximum increase of nearly 16%. The axial force in the column structural elements also experienced a significant rise, with a maximum percentage increase of around 89%, as shown in Table 12.

6. CONCLUSION

Based on the evaluation of a building structure with differential settlements and structural analysis, the following conclusions were drawn:

1. The settlement measurement of the existing building is nearly six times the allowed limit (1/300), indicating a critical condition in which structural collapse could occur.
2. The effect of differential settlement loads results in an increase in internal forces in the beams, such as a 16% increase in moment and shear capacity, while the internal forces in the columns experience a decrease in maximum axial force of 89%.
3. Due to the additional load from the building settlement, almost all existing structural elements, such as columns and beams, do not meet current Indonesian building codes. Consequently, the differential settlement reduces their capacity. It is recommended that the building not be used or converted for other activities and that it be demolished instead.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] Pratama G. A. P., Amornfa K., Mairaing W., and Soralump S., Investigation of differential settlement of pagoda foundation using 3D finite element method, International Journal of GEOMATE, Vol 26, Issue 113, 2024, pp. 10-18.

[2] El Naggar A., Youssef M. A., El Naggar H., El Ansary A. M., Differential Settlement Effect on RC Framed Structures, in Proc. of the Canadian Society of Civil Engineering Annual Conference 2021, pp. 683-694.

[3] Chen W. and Hanna A., Experimental investigation on structural response of multi-story buildings subjected to differential settlement of its foundations, Int. J. of Structural Integrity, Vol. 14 No. 2, 2023, pp. 204-228.

[4] Hanna A. and Chen W., Response of multistory steel structure subjected to differential settlements of its foundation, Int. J. of Structural Integrity, Vol. 13 No. 4, 2022, pp. 594-610.

[5] Miano A., Mele A., Prota A., Fragility curves for different classes of existing RC buildings under ground differential settlements, Engineering Structures, Vol. 257, 2022, No. 114077.

[6] XiaoTong Ma, Chao Bao, Haodong Shang, Huxiang Wang, Shu Ing Doh, Jun Hu, Hongbo Shu, Structural response of RC frame under surface curvature and differential settlement in mining areas, Physics and Chemistry of the Earth, Parts A/B/C, Vol. 128, 2022, No. 103239.

[7] Přikryl R. and Snížek P., Critical assessment of the “non-destructiveness” of Schmidt hammer test on monumental sandstones: A microscopic and microstructural approach, Journal of Cultural Heritage, Vol. 59, 2023, pp. 247-254.

[8] Indonesian National Standardization Agency, Geotechnical Design Requirements, SNI 8640:2017, BSN Jakarta, 2017, pp. 1-178.

[9] Indonesian National Standardization Agency, SNI 1726:2019 Seismic Resistance Design Codes for Building and Other Structures, BSN, Jakarta, 2019, pp.1-238.

[10] Indonesian National Standardization Agency, SNI 2847:2019 Structural Concrete Requirements for Buildings, BSN, Jakarta, 2019, pp.1-695.

[11] Indonesian National Standardization Agency, SNI 1727:2020 Minimum Load for Planning of Buildings and Other Structures, BSN, Jakarta, 2020, pp.1-302.

[12] Fauzan, Ismail F. A., and Jauhari Z. A., Seismic Retrofitting Analysis Using Concrete Jacketing and Shear Wall on Dental Hospital Building of Andalas University, IOP Conf. Ser.: Mater. Sci. Eng., Vol. 602, No. 012108, 2019, pp.1-12.