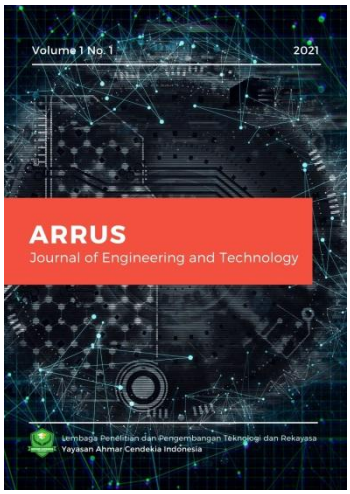
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RESEARCH ARTICLE

Vulnerability Assessment of Residential Structures Subject to Settlement for Adaptive Housing Design

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Abstract: This study aims to analyze the structural response and geotechnical conditions of a timber housing concept as a technical basis for developing adaptive housing designs resilient to land subsidence and climate change in the archipelagic region of Riau Islands Province. The research method integrates structural analysis using ETABS software and geotechnical analysis using PLAXIS. ETABS modeling was used to obtain the maximum load transferred to the foundation system, while PLAXIS was utilized to evaluate soil deformation and settlement based on the subsoil parameters at the study location. The analyzed foundation configuration consists of an isolated footing measuring 2.00 m × 2.00 m with a thickness of 0.15 m. The ETABS analysis revealed a maximum load of 45.54 kN/m², which was subsequently used as input for the PLAXIS analysis considering soil and foundation parameters. The results showed that the maximum subsoil settlement was less than 25 mm, thereby meeting the allowable settlement criteria for shallow foundations. Consequently, the subsoil does not require ground improvement via soil replacement. These findings demonstrate that integrating structural and geotechnical analyses on lightweight wooden housing structures provides a reliable technical foundation for developing adaptive housing through adjustments in building elevation, foundation systems, drainage, and environmental protection elements.

Keywords: Adaptive Housing, Settlement, ETABS, PLAXIS, Shallow Foundation,

1. Introduction

Climate change and environmental dynamics are an increasingly important challenge in the development of residential areas, particularly in island and coastal regions. Changes in rainfall patterns, sea level rise, increased flooding and inundation events, and changing environmental conditions can put pressure on the sustainability of housing. These impacts become even more complex when they occur together with land subsidence. Land subsidence lowers the ground surface elevation relative to sea level, which can increase the potential for inundation, tidal flooding, drainage system disruption, and damage to buildings and settlement infrastructure.

Land subsidence is a process of vertical deformation of the ground surface that can be caused by various factors, including soil layer consolidation, geological and geotechnical

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characteristics, building loads, groundwater extraction, and human activity. In residential areas, gradual land subsidence can change building elevation relative to the surroundings. This condition can cause various problems for buildings, such as wall cracks, floor deformation, drainage system disruption, changes in building tilt, and reduced foundation system performance. The level of impact varies depending on soil characteristics, building construction, environmental conditions, and the building's ability to adapt to these changes.

Climate change places additional pressure on housing conditions. Sea level rise raises the water level relative to the land, while changes in rainfall patterns and intensity can increase the potential for runoff and inundation. When sea level rise occurs in a region that also experiences land subsidence, the change in water level relative to the land surface can proceed faster. This condition can increase housing exposure to flooding, inundation, and environmental moisture, and can reduce the safety, comfort, and sustainability of housing.

Riau Islands Province has the geographic character of an archipelagic region, with many residential areas developing around coastal areas. This geography means that community activities and housing development are closely tied to the coastal environment and sea level dynamics. The growth of residential areas and the demand for housing land can cause construction to take place in areas with differing environmental characteristics. Therefore, land subsidence and climate change need to be considered in housing development so that buildings not only meet current space needs but are also able to withstand future environmental changes.

The vulnerability of housing to land subsidence and climate change is determined not only by the level of hazard but also influenced by the level of exposure, building sensitivity, and adaptive capacity. Physical factors such as floor elevation, foundation system, structural condition, building materials, drainage condition, building age, and site characteristics can influence housing vulnerability. Therefore, an approach is needed that connects environmental conditions with building characteristics so that housing vulnerability can be identified more comprehensively.

One approach that can be used to reduce the impact of these changing environmental conditions is the application of the adaptive housing concept. Adaptive housing is a building concept designed to adjust to changing environmental conditions and reduce the impacts of environmental hazards. Design strategies can include raising the building floor elevation, adjusting the foundation system to soil conditions, using materials suited to the environment, improving the drainage system, and applying building elements that allow adjustment or modification when environmental conditions change.

In this study, timber housing is used as the initial concept of a housing form that is developed into adaptive housing. The use of timber construction is considered because of its relatively light and flexible character and because it allows a construction system that can be adjusted to environmental conditions. This initial concept is not treated as the final design but is developed based on the results of the vulnerability analysis of land subsidence and climate change. Design adjustments can cover building elevation, foundation system, structural configuration, material selection, access system, and protection elements against inundation and flooding.

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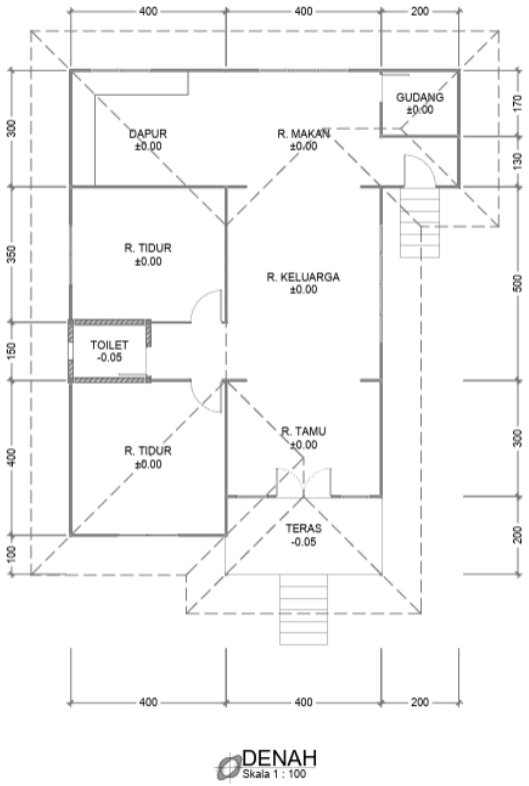


Figure 1. Timber Housing Floor Plan



Figure 2. Initial Timber Housing Concept Developed as the Basis for Adaptive Housing Design

This initial housing concept then becomes the basis for developing a design that is more responsive to environmental conditions. With this approach, the housing design considers not only architectural aspects and spatial function but also the level of risk faced by the building. The higher the vulnerability of a site, the greater the need for adaptation strategies in terms of elevation, foundation, structure, materials, and building protection systems.

A number of previous studies discuss land subsidence, climate change, coastal area vulnerability, and building adaptation strategies. However, studies that integrate land subsidence, climate change, the physical characteristics of housing, and adaptive housing design development in one research framework, particularly for the characteristics of the Riau Islands region, still need to be developed. Research that links vulnerability analysis results with housing design parameters is needed so that studies do not stop at identifying risk levels

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but can produce design solutions that can be applied to housing in regions facing changing environmental conditions.

Based on these problems, this study aims to analyze the level of housing vulnerability to land subsidence and climate change in the Riau Islands, identify the factors that influence that vulnerability, and develop an adaptive housing design concept based on the results of the vulnerability analysis. The results are expected to provide a scientific basis for developing housing that is more resilient to changing environmental conditions and to serve as input for planning and developing adaptive residential areas in the Riau Islands.

2. Literature Review

Climate change and land subsidence are a dual challenge that threatens the structural integrity and long-term sustainability of coastal and island settlements worldwide. In island regions such as Riau Islands Province, these environmental pressures reinforce each other's effect on vulnerability through sea level rise, extreme changes in rainfall patterns, and reduced bearing capacity of the subgrade (As-syakur et al., 2023; Bott et al., 2021). Land subsidence—triggered by natural soil consolidation, geological characteristics, building loads, and groundwater extraction—causes a gradual lowering of the surface elevation (Abidin et al., 2013; Susilo et al., 2023). When it interacts with climate-induced sea level rise, this physical deformation increases the risk of tidal inundation (rob), disrupts regional drainage networks, and causes differential settlement in building structures (Hamdani et al., 2022). Therefore, a deep understanding of the geotechnical and structural response of buildings to this combined hazard is essential for disaster risk mitigation and resilient infrastructure development (Intergovernmental Panel on Climate Change [IPCC], 2022).

The structural vulnerability of housing in coastal areas is closely related to the mechanical behavior of the subgrade soil layers under environmental loading scenarios. In geotechnical engineering practice, evaluating shallow foundation settlement requires an integrated numerical analysis approach to represent soil–structure interaction accurately (Bowles, 1996; Coduto et al., 2011). Advanced geotechnical modeling using the Finite Element Method, such as PLAXIS software, enables simulation of stress distribution, soil displacement, and consolidation mechanisms under structural loads (Das & Sobhan, 2018; Terzaghi et al., 1996). On the other hand, structural analysis software such as ETABS provides precise estimates of the internal force response and the maximum loads (dead load, live load, and environmental load) transferred to the foundation system. Integrating these two analysis tools forms a comprehensive design verification framework, linking the needs of structural engineering analysis with the tolerance limits of soil mechanics (Badan Standardisasi Nasional, 2017, 2020).

As an effort to minimize the dual impact of land subsidence and climate change, the adaptive housing concept is a strategic approach that is widely developed. Adaptive housing emphasizes flexibility, light structural weight, adjustment of building elevation, and selection of materials resistant to environmental conditions without large-scale soil improvement (Sari et al., 2025). Timber construction inherently offers performance advantages on soft soils or in subsidence-prone areas because of its high strength-to-weight ratio and structural flexibility, which significantly reduce the vertical load on shallow foundations (Badan Standardisasi Nasional, 2013). Recent research shows that lightweight timber-structure housing integrated with raised elevation and a good drainage system offers a sustainable solution for coastal communities (Hamdani et al., 2022; Sari et al., 2025). Based on this understanding, this study applies integrated ETABS–PLAXIS modeling to analyze the structural safety and geotechnical deformation of the timber housing concept in the Riau Islands, in order to provide a technical basis for developing adaptive housing designs in island regions.

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3. Research Method and Materials

This study uses a quantitative approach through numerical analysis to evaluate the response of the housing structure to soil conditions and potential land subsidence. The study integrates structural analysis using ETABS software and geotechnical analysis using PLAXIS. The ETABS analysis is used to obtain the structural response and the maximum load acting on the housing structure, while the PLAXIS analysis is used to evaluate the soil response to that loading, particularly the magnitude of soil deformation or settlement.

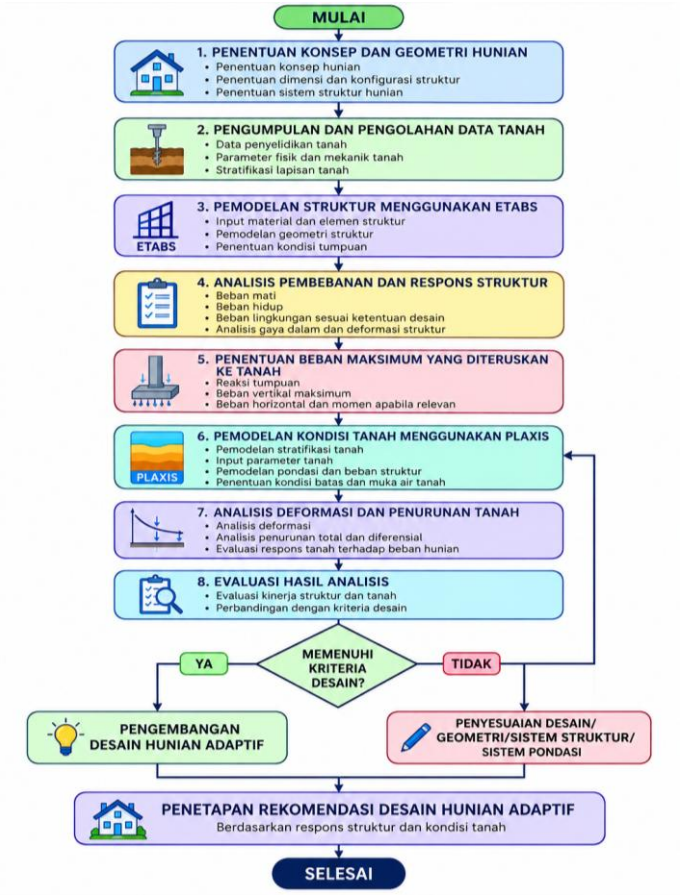


Figure 3. Research Flowchart

3.1. Research Location and Data

The study is conducted in an area that serves as a case study in Riau Islands Province. The data used include housing design data, material and structural dimension data, and soil characteristic data at the study site. Structural data include building geometry, structural element dimensions, material types, dead loads, live loads, and other loads relevant to building conditions. Meanwhile, soil data include soil layer stratification, unit weight, cohesion, internal friction angle, modulus of elasticity, Poisson's ratio, permeability, consolidation parameters, and groundwater conditions. The soil data are used as parameters in geotechnical modeling using PLAXIS, while the structural data are used to build the housing model in ETABS.

3.2. Structural Modeling and Analysis Using ETABS

Structural modeling is performed using ETABS software based on the predetermined timber housing concept. The structural model is created by entering the building geometry, structural element dimensions, material characteristics, support conditions, and loads acting on the

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building. The loads considered include dead load, superimposed dead load, live load, and relevant environmental loads. All loads are then combined according to the loading conditions used in the analysis. The ETABS analysis results are used to obtain the structural response, particularly the support reactions and the maximum load transferred by the structure to the foundation system. This maximum load value is then used as the loading input in the geotechnical analysis using PLAXIS.

3.3. Soil Modeling and Analysis Using PLAXIS

The geotechnical analysis is performed using PLAXIS software with the Finite Element Method (FEM). The soil modeling is based on the soil layer conditions and geotechnical parameters at the study site. The PLAXIS model consists of soil layers, groundwater conditions, the foundation system, and the structural load obtained from the ETABS analysis. The analysis proceeds in stages, from the initial soil condition, the generation of the initial stress state, and foundation installation, to the application of the structural load. The analysis results are used to obtain the deformation and soil settlement values due to the housing load. The main parameters observed include total settlement and maximum settlement.

3.4. Evaluation and Development of Adaptive Housing Design

The structural analysis results from ETABS and the soil settlement results from PLAXIS are used to evaluate the performance of the housing design. The settlement value obtained is compared with the settlement limit used as the evaluation criterion. If the analysis results show settlement or structural response that does not meet the criteria, adjustments are made to the design, such as the foundation system, foundation dimensions, building elevation, structural configuration, and load distribution. The evaluation results are then used as the basis for developing an adaptive housing design that considers soil conditions, land subsidence, and the impacts of climate change. Thus, the final housing design considers not only structural aspects but also the building's ability to adapt to changing environmental conditions.

4. Results and Discussion

4.1. Structural Modeling Using ETABS

The housing structural modeling is performed using ETABS software based on the predetermined initial timber housing concept. Three-dimensional modeling is performed by entering the building geometry, structural element dimensions, material characteristics, support system, and loads acting on the building.

The loads used include dead load, superimposed dead load, live load, and other loads relevant to housing conditions. The analysis is performed to obtain the structural response and the load transferred to the foundation system.

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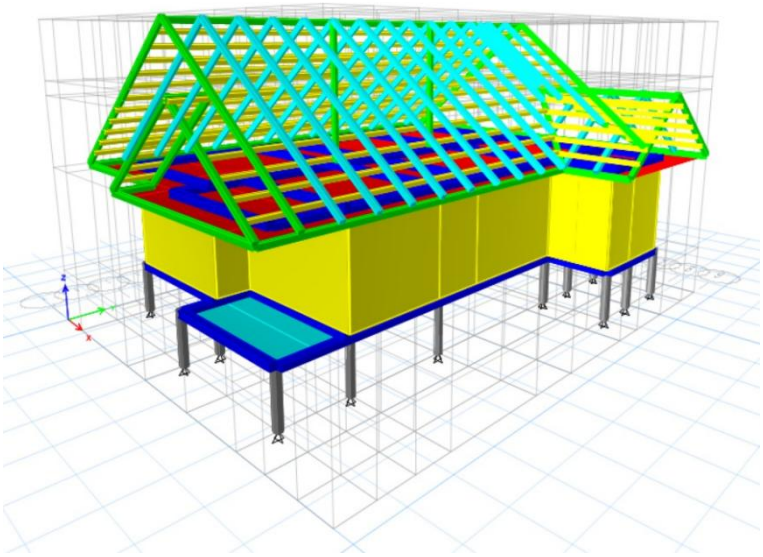


Figure 4. Housing Structural Modeling Using ETABS

Based on the ETABS analysis results, a maximum load of 379.37 kN is obtained. This value is then used as the basis for loading in the geotechnical analysis using PLAXIS to evaluate the soil response to the housing load.

4.2. Soil and Foundation Parameters in PLAXIS

The geotechnical analysis is performed using PLAXIS software with the subgrade soil parameters at the study site. The subgrade is modeled according to the conditions and characteristics of the soil layers based on the available geotechnical data. The soil parameters used in the modeling include soil unit weight, cohesion, internal friction angle, modulus of elasticity, Poisson's ratio, permeability, and other parameters required by the soil material model used. In addition to the soil parameters, the PLAXIS model includes foundation parameters according to the housing design analyzed.

Table 1. Foundation Parameters Used in PLAXIS

PLAXIS Parameter	Foundation	Unit
Material model	Linea Elastic	—
Drainage type	Non-Porous	—
γunsat	24	kN/m³
γsat	-	kN/m³
Eref	20000000	kN/m²
ν	0.15	—

Table 2. Soil Input Parameters in PLAXIS

PLAXIS Parameter	Soil	Unit
Material model	Mohr-Coulomb	-
Drainage type	drained	-
γunsat	14	kN/m³
γsat	15	kN/m³
E'	1500	kN/m³
ν	0.35	-
c'	1	kPa
φ'	3.23°	°
kx	1×10^{-8}	m/s
ky	1×10^{-8}	m/s

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The soil and foundation modeling is then performed based on the existing conditions at the study site. The maximum load of 379.37 kN obtained from the ETABS analysis is applied to the foundation system to determine the soil deformation and settlement due to the structural loading.

4.3. *Geometry and Soil Modeling in PLAXIS*

The PLAXIS model geometry is created to represent the soil conditions and foundation system at the study site. The model consists of the soil domain, subgrade layers, the foundation, and the structural load acting on the foundation. The model domain dimensions are determined such that the model boundaries do not significantly affect the stress distribution and deformation around the foundation.

The soil layers in the model are arranged based on the stratification and depth of the soil layers obtained from the geotechnical data. Each layer is assigned material parameters according to its soil characteristics. The foundation is then placed at an elevation and depth according to the housing design analyzed.

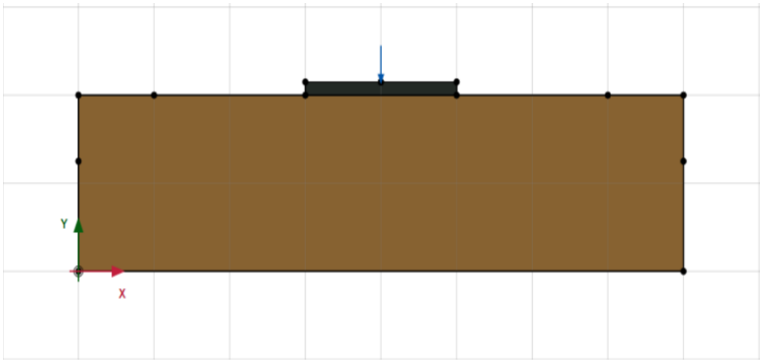


Figure 5. Soil and Foundation Model Geometry in PLAXIS

In the modeling, the lateral and bottom boundaries of the model are determined according to the boundary conditions used in the finite element analysis. The bottom of the model is restrained to prevent vertical displacement, while the lateral boundaries are used to restrain horizontal displacement. The ground surface is used as the top boundary of the model and is the location where the structural load is applied.

4.4. *Settlement Analysis Results*

The PLAXIS analysis results show that the maximum settlement occurring in the subgrade is 22 mm.

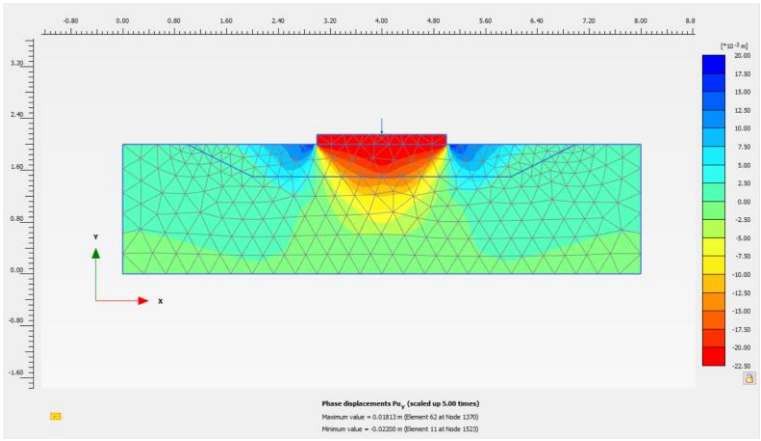


Figure 6. Soil Deformation and Settlement Analysis Results Using PLAXIS

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The settlement value is then compared with the settlement limit used in the study, namely 25 mm for shallow foundation evaluation. Based on the analysis results, the maximum settlement value is below that limit, so the subgrade condition meets the settlement criterion used. These results show that the maximum load of 379.37 kN transferred by the structure is still acceptable to the modeled soil and foundation system without producing settlement that exceeds the evaluation limit. This condition also shows that in the analyzed model no soil improvement through soil replacement is needed, because the existing subgrade already provides a settlement response that meets the criterion. Thus, the design can be developed using existing soil conditions without requiring replacement of the soil layer.

4.5. Discussion and Development of Adaptive Housing Design

The ETABS and PLAXIS analysis results show that the analyzed housing concept provides a response that meets the structural and geotechnical criteria used. The maximum load of 379.37 kN obtained from ETABS is used as the load on the foundation system, while the PLAXIS analysis results show a maximum settlement of <25 mm. The use of the timber housing concept offers the advantage of a relatively light structural weight, so the load transferred to the soil can be controlled. Based on the subgrade analysis results, this condition does not produce settlement that exceeds the limit used in the study. Although the subgrade meets the settlement criterion, the housing concept still needs to be developed with consideration of adaptation to environmental change. Adaptation can be applied through raising the building elevation, selecting an appropriate foundation system, using materials resistant to humid environments, a good drainage system, and ease of modifying the building in response to changing environmental conditions.

Thus, the structural and geotechnical analysis results serve as the technical basis for developing the adaptive housing design. A subgrade condition that meets the criteria allows the housing design to be developed without soil replacement, while the relatively light character of the timber structure can be maintained as one strategy to reduce the load on the soil.

5. Conclusion

Based on the results of the structural analysis using ETABS and the geotechnical analysis using PLAXIS for the timber housing concept in Riau Islands Province, it can be concluded that:

(1). The structural analysis results using ETABS show that the maximum load transferred to the foundation system is 379.37 kN. This value is used as the basis for loading in the geotechnical analysis using PLAXIS.
(2). Based on the PLAXIS modeling using the subgrade soil parameters and foundation parameters according to the study conditions, a maximum settlement value of 22 mm, less than 25 mm, is obtained. This value is below the settlement limit of 25 mm used as the evaluation criterion for shallow foundations, so the analyzed subgrade condition and foundation system meet the settlement criterion.
(3). The structural and geotechnical analysis results show that the timber housing concept can be developed as adaptive housing, taking into account the relatively light structure and the subgrade condition that meets the settlement criterion. Further design development can be directed toward raising the building elevation, an appropriate foundation system, protection against inundation, a drainage system, and selection of materials suited to environmental conditions.
(4). Integrating the ETABS and PLAXIS analyses provides a technical basis for developing the adaptive housing design, because the structural load can be evaluated first and the soil response to that load can then be checked through deformation and settlement analysis.

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