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SUSTAINABLE HOUSING CONSTRUCTION ON SLOPED TERRAIN: STRUCTURAL INNOVATIONS

Arkadi Zakharov[1*], Tatiana Zabalueva[1]

[1*]*Moscow State University of Civil Engineering, Moscow, Russia;*

[*]Corresponding Author Arkadi Zakharov, e-mail: zakharov.arkady@yandex.ru;

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ABSTRACT

This article examines the challenges of constructing individual residential buildings on sloped terrain, emphasizing both structural efficiency and environmental sustainability. It provides a brief overview of traditional solutions used in such construction, evaluating their cost, effectiveness, and ecological impact. New approaches to building houses on sloped terrain using a modern structural system, the "load-bearing floor," are proposed. This system, in which the second floor functions as a spatial structure composed of rigidly connected floor slabs along with external and internal walls, minimizes land disruption and reduces material consumption. The advantages and limitations of this system are analyzed, highlighting its potential to lower construction costs, enhance the strength and stability of buildings, and expand compositional and architectural flexibility. Additionally, by eliminating the need for extensive excavation and reducing the footprint of foundations, the system helps mitigate soil erosion and preserves the natural landscape. The use of lighter, optimized materials also contributes to improved energy efficiency and reduced carbon emissions during both construction and operation. The system further enables the creation of a lower floor free from intermediate supports, accommodating diverse planning requirements without restricting the architect's creative vision. Moreover, its flexibility for future remodelling and spatial reconfiguration supports sustainable, long-term residential use, reducing waste associated with demolition and reconstruction. Through these innovations, the proposed system addresses both the practical and ecological challenges of residential construction on sloped terrain.

Keywords: structural system "load-bearing floor", Sustainable construction, spatial structure, steel-reinforced concrete, compositional solutions, flexibility in planning, possibility of future remodelling.

INTRODUCTION

The issue of carbon footprints is central to all industries, including construction, which remains one of the largest contributors to global greenhouse gas emissions. As the urgency of climate change mitigation grows, the construction industry is increasingly shifting its focus toward sustainable solutions that reduce its environmental impact (Fatima, 2024). The adoption of greener technologies in building design, material production, and operational efficiency has become a defining trend, with the residential sector leading this transformation (Ilyushin and Afanaseva, 2020). According to the International Finance Corporation (IFC) report Building Green in Emerging Markets (International Finance Corporation, 2023), buildings account for nearly 40% of global energy-related CO_2

emissions and 50% of all extracted materials. With urban populations expanding rapidly, particularly in emerging markets, global demand for housing is projected to double by 2060. This makes sustainable construction not only an environmental necessity but also a critical economic and social priority (Glebova et al., 2022). The integration of energy-efficient materials, waste-reducing construction methods, and optimized structural designs can significantly lower both a building's carbon footprint and its operational costs (Ilyushin and Martirosyan, 2024; Qing and Li Na, 2024). Residential construction on sloped terrain presents both significant challenges and unique opportunities (Litvintseva and Dorofeeva, 2019). Traditional construction methods often require extensive excavation, large foundations, and high material consumption, all of which contribute to environmental degradation, soil erosion, and increased CO_2 emissions (Kanchanawongpaisan and Yan, 2025). Additionally, in seismically active regions, sloped terrain is prone to landslides and structural instability, further complicating the construction process (Subbotin, 2008). The 1988 Spitak earthquake in Armenia, one of the most devastating earthquakes in the late Soviet period, underscored the importance of resilient building designs, as the disaster led to the collapse of numerous buildings and significant loss of life. Despite these challenges, a substantial portion of sloped areas remains suitable for residential construction. In Russia, approximately 40% of the total land area consists of mountainous regions, and as urban expansion continues, previously undeveloped sloped land is increasingly being allocated for residential use (Kan, 2018). However, existing construction regulations—such as SNiP 2.07.01-89*, which recommends slopes up to 30° for construction—pose technical constraints that necessitate innovative building solutions. The demand for cost-effective, structurally resilient, and environmentally sustainable approaches has never been more pressing. Given these factors, this study explores the "load-bearing floor" system as a sustainable and structurally efficient alternative for residential construction on sloped terrain. This system, in which the second floor acts as a spatially rigid structure composed of interconnected floor slabs, external walls, and internal partitions, offers multiple advantages (Masrom and Abdul Hamid, 2023). It reduces material consumption, minimizes structural weight, and optimizes construction costs, all while enhancing earthquake resistance and adaptability to sloped landscapes (Khakimov et al., 2024). Furthermore, the "load-bearing floor" system significantly reduces environmental impact by limiting excavation and foundation requirements, preserving the natural topography, and integrating lightweight, high-performance insulation into a three-layer external wall system (Stindt et al., 2024). These design elements improve thermal efficiency, reducing energy consumption for heating and cooling, thereby contributing to lower carbon emissions over the building's lifecycle (Küpfer et al., 2024). By offering greater flexibility in spatial planning, the system accommodates diverse architectural configurations and allows for future remodeling without the need for structural modifications. This adaptability not only supports long-term sustainability but also aligns with global efforts to promote low-carbon, resource-efficient construction practices (Elgohary et al., 2024).

MATERIAL AND METHODS

This study investigates the application of the "load-bearing floor" structural system in the construction of individual residential buildings on sloped terrain. The research was conducted at Moscow State University of Civil Engineering (Zakharov and Zabalueva, 2012) and involved both theoretical analysis and practical implementation. The system has been tested in the construction of over 30 houses, demonstrating its feasibility in real-world applications. Additionally, it is protected by patents (Zabalueva et al., 2014) and has been the subject of two candidate dissertations, further validating its structural reliability and innovative potential. This article examines the collected data, evaluates the practical results, and analyzes the applicability of the proposed system in terms of structural performance, environmental impact, and economic feasibility.

RESULTS AND DISCUSSION

The structure of houses utilizing the load-bearing floor system is made of monolithic steel-reinforced concrete (Evdokimov et al., 2013). In modern terminology, steel-reinforced concrete refers to conventional reinforced concrete, which contains rod and mesh reinforcement, in addition to steel rolled profiles such as angles, T-beams, channel sections, and other cross-sectional elements. Previously, this material was known as "reinforced concrete with rigid reinforcement." During the construction of houses of this type, flexible reinforcement with a diameter of 12 mm was used, along with wire mesh featuring a grid size of 150 × 150 mm and a wire diameter of 5 mm.

Additionally, rigid reinforcement was implemented using channel sections No. 8 and 40×3 mm steel angles. Together, these elements formed a steel framework within the reinforced concrete structural system, significantly enhancing the building's resistance to landslides and seismic activity (Nazarenko and Zakharov, 2018). As an example, Figure 1 illustrates the reinforcement scheme for a two-story house without a basement, featuring a free first floor and a load-bearing second floor. The figure highlights the vertical channel sections, which extend down to the foundation along the perimeter of the external walls at 2–3 m intervals, excluding window openings. Additionally, horizontal channel sections are placed along the perimeter of each floor slab and the foundation strip, forming a steel base within the reinforced concrete frame, thereby ensuring the structure's resistance to landslides and seismic impacts.

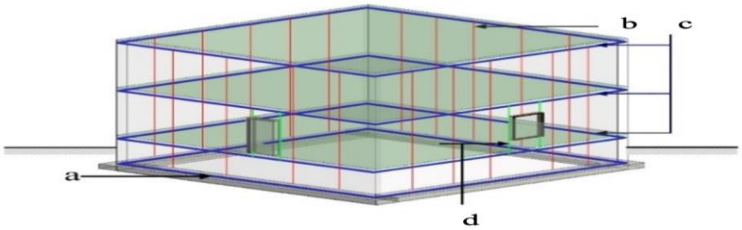

Figure 1. Structural reinforcement scheme of a house frame with rolled steel sections.

(a) – Channel section No. 8 positioned on the reinforced concrete strip foundation
(b) – Channel section No. 8 vertical posts, extending from the foundation
(c) – Channel section No. 8 forming the edges of reinforced concrete floor slabs, welded to the vertical posts
(d) – Examples of framed openings: door opening (left) and window opening (right) with 40×40 mm steel angles

To ensure the spatial rigidity of the second-floor framework in individual low-rise residential buildings, a single internal load-bearing wall is sufficient.

This wall spans the entire floor volume, connecting opposite external walls, and is firmly integrated with the lower and upper floor slabs (Figure 2).

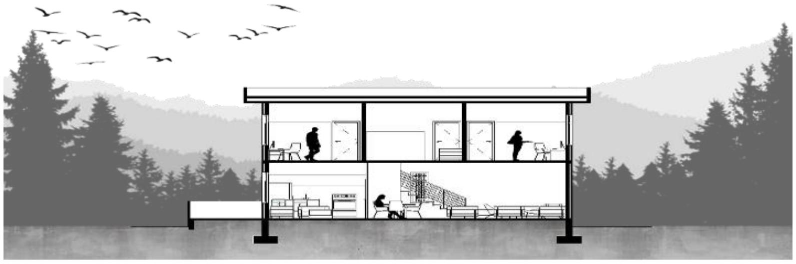

Figure 2. Internal Load-Bearing Wall for Spatial Rigidity.

Figure 2 shows a sectional view of the house in front of the wall along axis B of the load-bearing (second) floor. The remaining internal walls, which define the room layout on the second floor, may have limited length and be connected to only one external wall. Their arrangement is determined by the floor plan and room dimensions. The intersections of these walls can take L-shaped, T-shaped, or cruciform configurations. These intersections are rigidly connected to the floor slabs and, if necessary, can be reinforced with 4×4 cm steel angles.

As a result, all internal walls work in conjunction with the floor slabs, forming a rigid, strong, and stable spatial framework for the load-bearing second floor (Figure 2). This structural approach provides architects with significant flexibility in designing floor layouts, with the sole restriction that room dimensions should not exceed 4 × 4 meters, or 3 × 6 meters. These limitations are imposed to prevent unwanted deflections in the floor slabs and to avoid increasing slab thickness (which is currently 100 mm). Exceeding these dimensions would require thickening the floor slab, which may compromise the efficiency of the structure. All internal walls may include doorways and other openings. Above doorways in internal walls, there are lintel sections approximately 1 meter in height. These openings are framed with steel angles, which are anchored into the floor slabs. Additionally, doorways within internal walls should be positioned no closer than 1–1.5 meters from external walls. This is essential to maintain structural rigidity and load-bearing capacity, as key tensile force lines pass through these zones, and maximum transverse stresses develop here. To prevent deflection of the floor slabs, all internal walls are reinforced using: Class AIII steel rods (Ø 12 mm), T-shaped end elements, anchored in the floor slabs. These elements function as hangers, spaced at 1-meter intervals. These reinforcements ensure that walls with openings retain sufficient strength to withstand expected structural loads (Nazarenko and Zakharov, 2018; Saud and Zabalueva, 2018, 2019). This steel-reinforced concrete system is highly effective in mountainous terrain, where landslides and seismic activity present significant challenges. The spatial integration of the entire structural system enhances its stability and overall strength, improving the structural resilience of the house. By reducing the thickness of floor slabs and internal walls in the load-bearing floor, and eliminating internal load-bearing walls and foundations in the free floor, the weight and cost of the structural frame of the house can be reduced by up to 30%. Additionally, the three-layer external wall construction, which incorporates insulation, provides high thermal efficiency, ensuring heat retention during winter, and protection from direct solar radiation in summer. From an architectural and planning perspective, the system enables the creation of a first floor free from intermediate supports, allowing flexible floor plan configurations to meet customer requirements, greater creative freedom for architectural design, and cost-effective and straightforward redevelopment of the lower floor, if needed, without altering the load-bearing frame. This flexibility is particularly valuable for long-term operation of permanent residential structures, where modifications may be required over time (Malka et al., 2022; Nazarenko and Zakharov, 2016). On the second load-bearing floor, the dimensions of individual rooms are subject to the constraints outlined earlier. Any increase in these dimensions would necessitate an increase in floor slab thickness, which in turn would raise the overall construction cost. However, the total floor area of the second story can be increased or reduced on one or two (opposite) sides. This design flexibility enables the creation of diverse summer spaces, improving the overall architectural composition of the house (Figure 3).

Figure 3. Expansion of the second floor area.

This figure illustrates an example of increasing the second-floor footprint relative to the first floor, with the creation of a shaded space beneath the extended section. The load-bearing floor system presents not only structural advantages but also significant ecological benefits, making it a sustainable alternative to traditional construction methods, particularly in mountainous and sloped terrains. By reducing the thickness of floor slabs and internal walls, as well as eliminating unnecessary internal load-bearing walls and foundations, this system achieves a lighter structural frame, leading to a 30% reduction in material consumption and overall construction costs. This reduction translates into lower carbon emissions associated with material production, transportation, and on-site construction activities (Hafez et al., 2023). Furthermore, the three-layer external wall system significantly enhances thermal efficiency, contributing to lower energy consumption for both heating and cooling. In winter, the high-performance insulation helps retain heat, reducing the reliance on fossil fuel-based heating systems, while in summer, it minimizes solar heat gain, decreasing the need for air conditioning. This passive energy-saving approach aligns with global efforts to reduce greenhouse gas emissions and transition toward sustainable, energy-efficient housing solutions. Beyond energy efficiency, the system also offers environmental benefits by minimizing land disruption. Traditional construction on sloped terrain often requires extensive excavation and large concrete foundations, which can destabilize the soil, increase erosion risks, and disrupt local ecosystems. The load-bearing floor system, by contrast, reduces the footprint of deep foundations, allowing the natural landscape to be preserved while maintaining structural resilience in challenging conditions. From an architectural standpoint, this construction method enhances design flexibility, allowing for adaptable layouts and cost-effective modifications over time without requiring structural alterations. This adaptability is particularly valuable for long-term residential use, as housing needs evolve due to family expansion, lifestyle changes, or climate adaptation. The system's ability to extend or reduce the second floor's footprint without compromising stability or energy efficiency further demonstrates its suitability for sustainable residential architecture. The load-bearing floor system not only improves construction efficiency and seismic resistance but also supports sustainability goals by reducing material waste, energy consumption, and land disturbance. By integrating modern engineering innovations with eco-conscious design principles, this approach represents a practical and forward-thinking solution for residential construction in challenging terrains. As the demand for sustainable housing solutions continues to grow, implementing such structural advancements can play a crucial role in reducing the environmental impact of future developments while ensuring cost-effective and resilient housing for generations to come.

CONCLUSIONS

- Based on the results of conducted research and extensive practical testing, the load-bearing floor system is recommended for effective application in modern low-rise residential construction on sloped terrain.
- The proposed system offers several key advantages, including expanded architectural and planning capabilities for individual residential buildings, allowing for greater flexibility in design and layout. Additionally, it significantly reduces construction costs by optimizing the structural weight, making the building process more efficient. The system also provides enhanced thermal protection, ensuring better insulation and resistance to overheating, which contributes to improved energy efficiency. Another important benefit is the feasibility of step-by-step or phased construction, allowing for gradual development without compromising structural integrity. Furthermore, the system enables flexible redevelopment of the lower floor, making it possible to adapt the space to changing needs over the long-term operation of the building.
- In light of climate change, urban expansion, and increasing construction demands, the need for innovative, ecologically responsible building solutions is more critical than ever. The "load-bearing floor" system represents a promising alternative to traditional sloped terrain construction, balancing structural resilience, cost-effectiveness, and environmental sustainability. Through its integration, the residential construction sector can make meaningful strides in reducing its carbon footprint while ensuring safe, durable, and energy-efficient housing for the future.

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