

# Evaluation of bearing capacity of conical foundations and conical models with a pile stand near the undermining territories

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**ABSTRACT:** Construction of buildings and structures near undermined areas is complicated by the risk of increased deformability of foundation soils, which often leads to failure of bearing capacity of soils. Even small values of horizontal soil displacements are dangerous and can lead to uneven settlement of foundations. A novel cone-top pile foundation system was developed to improve structural performance in undermined, seismic, and soft layered soils. Unlike traditional shallow isolated foundations, the proposed hybrid integrates an inverted cone with a central pile shaft and a rolling joint to enhance load transfer and accommodate horizontal strains. Laboratory, field, and PLAXIS 2D numerical simulations were conducted to assess bearing capacity, settlement behavior, and resistance to lateral deformation. Results indicate significantly reduced settlements and higher load-bearing capacity compared to isolated shallow foundations, especially under horizontal tensile strains. The design methodology, validated by experiments and finite element modeling, supports the conical or cone-top pile foundation as a practical solution for infrastructure in strain-prone geotechnical environments.

**KEYWORDS:** undermined territories, cone-top pile foundation, conical foundation, bearing capacity, soil–structure interaction.

## 1 INTRODUCTION

Undermined and strain-prone soils, such as those in the Karaganda coal basin, are prone to both vertical settlement and horizontal displacement due to mining-induced ground deformation (Osmanov&Tleukenov, 2019). These conditions often exceed the permissible deformation limits defined in Kazakhstani standards, leading to structural instability (Shashkin&Kenzhegaliyev, 2016). Conical foundations have previously demonstrated improved performance under horizontal tensile strains due to their geometry, which increases bearing capacity and reduces settlement (Zhussupbekov et al., 2024). However, limitations in lateral stability and resistance to extrusion remain. Mining subsidence, seismic events, and seasonal freeze–thaw cycles exacerbate deformation in these soils. Current foundation types often fail to reconcile the need for high bearing capacity with adaptability to horizontal movements. Previous studies in Russia, China, and Eastern Europe on conical and block foundations provided valuable insight but showed inadequate performance under combined vertical–horizontal load scenarios (Kratzsch, 1983; Litvinenko, 2012; Singh&Pal Roy, 2006). To address these issues, this study proposes a cone-top pile foundation that combines the advantages of a conical base for load dispersion and a central pile for deeper anchorage. The design further incorporates a rolling joint to mitigate stress transfer during soil movement, enhancing applicability in seismic and undermined zones.

## 2 MATERIALS AND METHODS

### 2.1 Foundation Concept

The cone-top pile foundation consists of an inverted conical base, a central pile shaft (diameter  $\approx 0.3$  of cone base diameter),

and a rolling joint interface between the superstructure and the foundation. This combination ensures effective vertical load distribution, increased lateral resistance, and minimized horizontal strain transfer (Zhussupbekov et al., 2025).

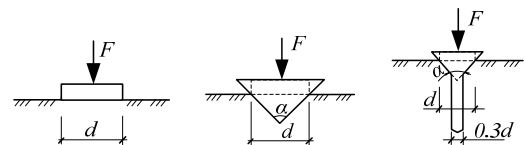


Figure 1. Shallow isolated, conical and cone-top pile foundations.

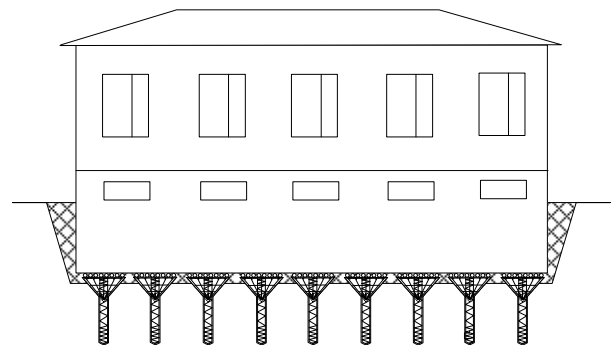


Figure 2. Cone-top-shaped pile foundation model.

To minimize the transmission of horizontal forces to the superstructure, the design incorporates a rolling joint—implemented as a double ball-bearing assembly mounted atop the foundation block (Figure 2). This mechanism efficiently counteracts the influence of horizontal soil strains on the building's upper structure by allowing relative movement

between the foundation and the superstructure. As a result, the configuration accommodates minor horizontal soil displacements caused by rock mass movements in the construction impact zone, thereby reducing structural stress and enhancing overall stability. As the surrounding soil settles, the cone's cross-section at the intersection with the ground surface increases, further improving the overall bearing capacity.

The study involved comprehensive laboratory tests on scaled models subjected to static loading under controlled horizontal soil displacement strains. Numerical modeling, fully aligned with laboratory conditions, was performed to simulate performance under varied soil properties. Field tests were conducted on a full-scale conical pile foundation model, incorporating measured horizontal displacements to replicate real operating conditions.

## 2.2 Laboratory Testing

To investigate the bearing capacity under controlled laboratory conditions, reduced-scale models of conical foundations with a pile stand were fabricated, as shown in Figure 3. These precision-made aluminum alloy models maintained geometric similarity to the full-scale design, with the pile diameter set at 0.3 of the cone base diameter. Testing was conducted on a dedicated laboratory bench capable of replicating horizontal soil displacement strains.

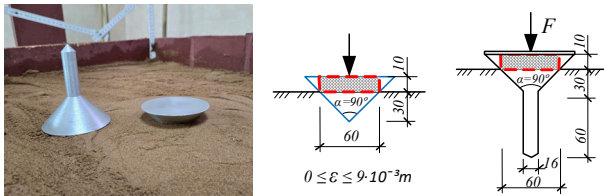


Figure 3. Laboratory testing with conical and pile stand conical models.

The models were installed within a specially designed three-dimensional expandable soil container, filled with an equivalent soil material uniformly compacted to match specified engineering properties. The container consisted of channel sections connected by bolts, with a continuous rubber seal at each joint to prevent soil leakage. By loosening the bolts, the rubber seal expanded horizontally, inducing controlled tensile strains of 3 mm/m, 6 mm/m, and 9 mm/m in the soil mass—simulating the convex tensile deformation zone near undermined area. This method accurately reproduced the conditions experienced in the AB zone of mining-affected areas, including settlement and potential microcrack formation in the foundation soil. A detailed description of the extendable box is provided in [3].

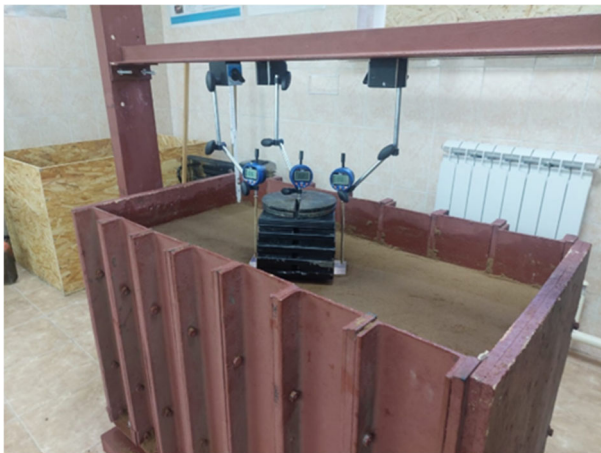


Figure 4. Laboratory testing with pile stand conical models.

The models were embedded into the pre-compacted soil compacted to replicate target geotechnical properties ( $c = 0.9$  kPa,  $\phi = 37^\circ$ ,  $E = 0.24$  MPa), so that the pile and cone penetrated to 0.7 of the cone height. Vertical loading was applied incrementally in 0.001 MPa steps using a calibrated hydraulic system. Each load step was maintained until settlement stabilized, defined as a deformation rate of less than 0.01 mm over 15 minutes. Testing continued until the applied pressure reached 16.7 N/cm<sup>2</sup>.

## 2.3 Field Testing

Full-scale steel prototypes were installed at a site in the Karaganda region (Figure 4), characterized by sandy loams over hard loams ( $c = 39$  kPa,  $\phi = 25^\circ$ ,  $E = 21.8$  MPa). A 3×3 m monitoring grid with benchmarks was established. Static loads were applied in  $12.5 \times 10^3$  N increments up to 100 kN. Settlements were measured at each stage until stabilization (<0.01 mm in 15 min). Tests were repeated under natural ground conditions and with induced horizontal tensile strains of  $\approx 2.7$  mm/m.



Figure 5. Cone-top-shaped pile foundation model.

For comparative evaluation of the bearing capacity between cone-top pile foundations and isolated shallow foundations, identical static loading tests were conducted using round plate indenters ( $A = 2462$  cm<sup>2</sup>), matching the top diameter of cone-top pile foundations at ground level. The circular plates ensured uniform load distribution, while 50 mm diameter steel balls mounted on a steel plate acted as a movable compensator, with their number selected to prevent exceeding the contact strength under the applied load.

## 2.4 Numerical Modeling

PLAXIS 2D axisymmetric analysis replicated laboratory and field configurations, employing the Mohr–Coulomb soil model. Domain dimensions extended 4–5 times the cone diameter to minimize boundary effects. Mesh refinement was concentrated at the cone–soil interface and pile tip. Loading stages matched experimental sequences. Simulations were run for strain values of 0, 3, 6, and 9 mm/m, allowing direct comparison with physical results (Figure 5).

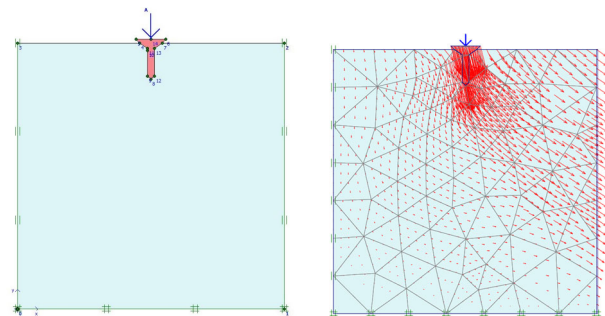


Figure 6. Numerical modelling of the conical foundation with 3, 6, and 9 mm/m horizontal displacement of the soil.

The soil domain in the simulation extended 4–5 times the cone diameter in all directions to minimize boundary effects.

Vertical boundaries were modeled as roller boundaries to restrict horizontal displacement, with the right boundary set to allow movement for simulating soil deformation, while the bottom boundary was fully fixed. The Mohr–Coulomb model was used for soil, and the conical foundation was defined as a linear elastic or rigid body, depending on stiffness assumptions. A refined mesh of 15-node triangular elements was applied around the cone–soil interface, especially near the tip and base, with a medium to fine global mesh for convergence. Static vertical loading was applied incrementally, and simulation outputs included settlement, vertical stress distribution, and plastic strain development.

### 3 RESULTS

#### 3.1 Laboratory Findings

Laboratory testing revealed that cone-top pile foundations exhibited consistently low settlement growth under increasing horizontal tension strains. At a load of 100 N, settlement increased from approximately 0.75 mm without strain to 0.90 mm at 9 mm/m strain. At a higher load of 200 N, settlement rose from 8.06 mm to 11.43 mm under the same range of strain. This gradual settlement increase indicates that the design effectively resists deformation even when subjected to tensile soil movements. In contrast, comparable conical foundations without a pile stand showed moderately higher settlements at each strain increment, while shallow foundations experienced rapid capacity loss, with settlements increasing sharply even at low strain levels of 3 mm/m.

Table 1. Results of the laboratory modeling for loading–settlement.

Foundation model type	Horizontal tension strain of soil, mm/m	Settlement under load, mm		
		100 N	150 N	200 N
Conical foundation with an aperture angle of 90 degrees	0	0.77	2.81	8.96
	3	1.05	3.52	10.38
	6	1.35	4.11	11.51
	9	1.58	4.72	12.62
Cone-top pile foundation	0	0.75	2.03	8.06
	3	0.80	2.80	8.95
	6	0.85	3.20	9.88
	9	0.90	3.88	11.43
Shallow isolated foundation	0	1.30	7.15	-
	3	1.53	11.08	-

Additional laboratory tests compared conical foundations with aperture angles of 90° and 80°, as well as columnar foundations. At 200 N without horizontal displacement, settlement was 11.50 mm for the 80° model and only 8.96 mm for the 90° model, indicating superior stiffness for the latter. Horizontal displacement of up to 9 mm increased settlement in the 90° model by about 3.66 mm, while the 80° model showed an increase of 3.65 mm over the same range. Columnar foundations lost bearing capacity after 140 N. Full results of load–settlement interactions for these models are given in Table 3, clearly showing the performance advantage of 90° conical models across all loading stages.

#### 3.2 Field Test Results

Field testing under site conditions at the Kostenko mine, with measured horizontal strains of approximately 2.6 mm/m, confirmed and extended the laboratory results. For a load of 100 kN, settlement for the 90° conical foundation was 8.25 mm without strain and 9.62 mm with strain, compared to 9.21 mm and 10.50 mm respectively for the 80° conical model. Columnar foundations failed at loads above 80 kN, exhibiting significantly lower bearing capacity. Overall, the bearing

capacity reduction under tensile strain was 13–14% for conical foundations and about 8% for columnar types. The results clearly show the advantage of conical foundations, with the 90° aperture angle demonstrating the highest load-bearing capacity and slower settlement growth. Under a 100 kN load, cone-top piles settled 8.52 mm without strain and 10.09 mm with 2.7 mm/m strain. Detailed data from the field trials are summarized in Table 2.

Table 2. Results of the field test for loading–settlement.

Foundation model type	Horizontal tension strain of soil, mm/m	Settlement under load, mm		
		50 kN	75 kN	100 kN
Conical foundation with an aperture angle of 90 degrees	0	3.21	5.72	8.25
	2.6	3.45	6.61	9.62
Cone-top pile foundation	0	3.49	5.01	8.52
	2.7	4.39	7.60	10.09
Shallow isolated foundation	0	3.70	8.4	-
	2.6	4.10	10.0	-

#### 3.3 Numerical Simulations

Numerical analysis reproduced experimental settlement–load curves with deviations under 5%. For cone-top piles, ultimate capacity exceeded test loads in all scenarios, and settlements under 9 mm/m strain remained within serviceability limits (Figure 7). Shallow foundations failed beyond 3 mm/m strain, confirming experimental observations (Table 3).

Table 3. Results of the laboratory modeling for loading–settlement.

Foundation model type	Horizontal tension strain of soil, mm/m	Settlement under load, mm		
		100 N	150 N	200 N
Conical foundation with an aperture angle of 90 degrees	0	0.75	2.65	9.54
	3	1.02	3.30	11.24
	6	1.32	3.90	12.19
	9	1.55	4.50	13.51
Cone-top pile foundation	0	0.75	1.90	8.40
	3	0.80	2.53	9.65
	6	0.85	3.16	10.75
	9	0.90	3.79	11.82
Shallow isolated foundation	0	1.30	7.25	-
	3	1.50	11.44	-

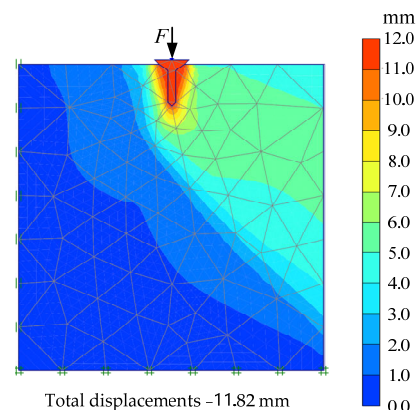


Figure 7. Laboratory testing with pile stand conical models

Two loading scenarios were modeled for isolated shallow foundations: without horizontal displacement and with a horizontal displacement of  $\epsilon = 3$  mm, the latter resulting in a loss of bearing capacity.

## 4 DESIGN SUMMARY

Bearing capacity calculations using Terzaghi's method and FEM confirmed a total capacity of 308.2 kN, against an applied load of 177.55 kN (FS  $\approx$  3). Estimated settlement, considering elastic and consolidation components, was 64 mm, acceptable for the soil profile tested. As shown in Figure 8, the reinforcement layout for conical foundations includes vertical bars made of reinforcing steel grade A500C (16 mm in diameter) distributed along the foundation height, fixed at the cone base with a 20 cm overhang at the sharp end. Transverse clamps of 8mm diameter are spaced at 15–20 cm at the top.

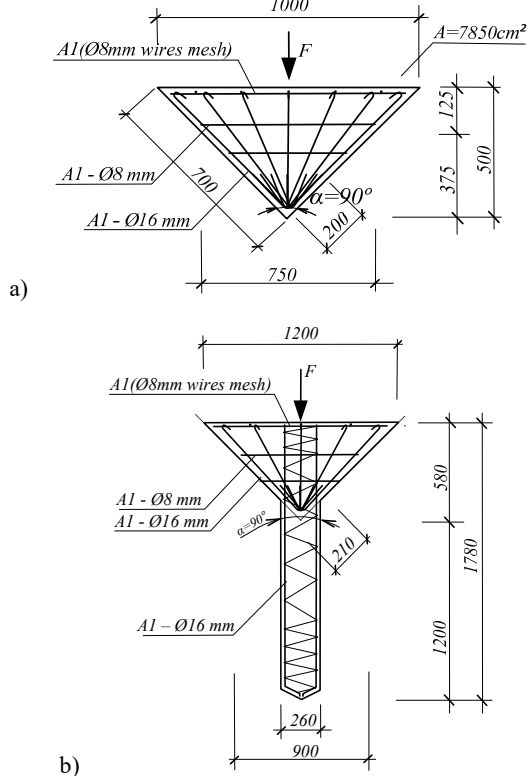


Figure 8. Reinforcement layout for conical foundations: (a) Conical block with an opening angle of 90°; (b) Cone-top foundation with a pile-stand.

The design of the conical foundation block utilizes heavy concrete of class B20, chosen for its high strength, load resistance, and durability under environmental conditions. The concrete is frost- and moisture-resistant, essential for installations in areas with high groundwater levels. Reinforcement is selected based on calculations of both vertical and horizontal loads, with vertical bars of A500C reinforcing steel (16–25 mm diameter) extending along the cone height and transverse clamps (8–12 mm diameter) spaced 15–20 cm apart, decreasing toward the cone base. Mesh reinforcement at the base enhances shear resistance, with denser spacing in high-stress zones, typically 15–20 cm mesh sides of A1 reinforcement (8–12 mm), adjustable to 10–16 mm in aggressive environments. A protective concrete layer of 40–50 mm safeguards the reinforcement from corrosion, and anti-corrosion coatings may be applied in aggressive conditions. The design incorporates calculations for resistance to horizontal displacement and shear forces, ensuring stability under industrial conditions. Examples include reinforcement layouts for a 500 mm height cone with a 1000 mm base diameter and a cone-top pile foundation of 1780 mm total length with a 1200 mm base diameter, both offering enhanced stability, reduced deformation, and extended service life.

## 5 PRACTICAL RECOMMENDATIONS

The following practical recommendations summarize optimal design and usage considerations based on research findings and experimental validation:

- Application Scope: Ideal for undermined territories, seismic zones, and soft layered deposits.
- Geometric Optimization: Use cone angles of 70°–90° and pile diameters  $\approx$  0.3 of cone diameter for balanced performance.
- Rolling Joint Implementation: Apply to minimize stress transfer from horizontal movements.
- Embedment Depth: Minimum of 3/4 cone height enhances lateral resistance and prevents extrusion.

## 6 CONCLUSIONS

This study evaluated a novel cone-top pile foundation that merges the load-spreading efficiency of a conical base with the deep anchorage of a central pile, linked by a rolling joint for adaptability and reduced stress transfer. Key conclusions are:

- Tests confirmed lower settlements and higher bearing capacity than shallow isolated or traditional conical foundations, especially under vertical loads and horizontal soil strain.
- PLAXIS 2D simulations matched experimental trends, capturing settlement behavior and stress concentration at the cone–pile–soil interface.
- Horizontal soil deformation increased settlements by up to 19%, but deeper embedment and geometry mitigated these effects. The rolling joint reduced stress transmission, improving performance in seismic, undermined, and layered soft soil conditions.
- The design enhances vertical and lateral load resistance, limits deformation, and maintains uniform stress distribution, making it well-suited for challenging soils.

## 7 ACKNOWLEDGEMENTS

Funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant AP13268861.

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