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A Systematical Review on Mechanisms of Soil Deformation Induced by Different Vertical Shaft Construction Methods

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Abstract. This paper reviews soil displacement induced by vertical shaft construction and compares downward and upward approaches using evidence from analytical solutions, numerical modelling and scaled tests. For downward excavation, cut-and-cover method generally produces trough-shaped surface settlement, with typical magnitudes of S_{max} = 0.1%~0.3%H (Where S_{max} is maximum settlement) and influence up to 1.5D(Where D as diameter), accompanied by cantilever-type wall lateral movement peaking at mid-depth. Diaphragm-wall shafts show parabolic wall deflection (often 4~6 mm) and settlement of 8~11 mm, while groundwater drawdown may amplify deformation by 30%~50%. Vertical shaft sinking method exhibits staged deformation with a convex-to-concave transition around 0.4~0.7H. For upward methods, they can limit surface settlement (<1mm) but intensify deep soil-structure interaction and crown dislocation risk.

Keywords: Downward excavation, Upward excavation, Soil deformation, Deformation mechanisms, Numerical modeling

1. Introduction

Rapid expansion of urban underground infrastructure to support transportation, water, energy, and environmental services has accelerated the adoption of vertical shaft construction. With recent progress in mechanization and intelligent equipment, shaft construction has become more flexible and efficient [1]. However, implementing shafts in dense urban settings remains technically demanding: soft ground often exhibits strong soil–water–structure coupling that necessitates reliable numerical modelling and timely field monitoring, while excavation-induced deformation can impact nearby structures and the urban environment [2].

Existing techniques are commonly categorized by construction direction into downward and upward excavation methods [3]. Downward shafts are typically formed by open excavation or by sinking-type approaches with structural support systems [4]. Upward methods, which can be advantageous where surface space is limited, include vertical pipe jacking, upward shield techniques, and vertical lift-up method [5].

This review investigates soil deformation induced by different shaft construction methods. Section 2 introduces representative shaft construction methods. Section 3 discusses the soil deformation drawing on analytical solutions, numerical simulations, scaled model tests. Section 4

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compares deformation characteristics and applicability across different methods. Section 5 presents practical recommendations and outlines directions for future research.

2. Different vertical shaft construction methods

2.1. Downward excavation methods

Downward excavation represents the conventional approach for shaft construction and is still widely adopted. It typically relies on staged excavation from the surface downward, together with retaining structures and internal bracing to limit ground disturbance. Representative methods include cut-and-cover method, diaphragm-wall method, and the vertical shaft sinking method.

2.1.1. Cut-and-cover method

The cut-and-cover method is a conventional open-excavation technique widely used for shafts. Its construction typically proceeds as follows: (1) installation of earth-retaining and water-control systems to provide stability; (2) groundwater control, including dewatering and the implementation of cutoff measures to lower the groundwater table and mitigate seepage-related instability; (3) staged excavation of the foundation pit, often using zoning or multi-level bracing to limit deformation, with soil removed by sloped open-cut or braced excavation depending on ground conditions; (4) installation and adjustment of support systems to resist lateral earth pressure during progressive excavation; and (5) construction of the permanent structure followed by backfilling, after which temporary works are removed and materials may be recycled where applicable [6,7].

2.1.2. Diaphragm wall

Diaphragm wall is a technology widely used in deep wells. Its deformation control performance is mainly determined by the stiffness of wall and embedded depth. The typical wall thickness ranges from 0.6 to 1.2 meters, and the embedded depth is usually 20 to 50 meters or even deeper. Construction is carried out in the following sequence: (1) construction of guide walls for positioning; (2) excavation of panel trenches under the support of bentonite slurry; (3) placement of steel reinforcement cages; (4) displacement of slurry by concrete pouring; (5) joint treatment to ensure water resistance [8].

2.1.3. Vertical Shaft Sinking Method (VSM)

VSM is an innovative mechanized method for shaft construction, particularly suitable for soft soi. The typical construction sequence includes: (1) assembling the machine and lowering it to the starting position; (2) mechanical excavation using a rotating cutter head, supported by slurry to maintain the stability of excavation; (3) installing shaft lining, usually using prefabricated segmental lining or cast-in-place concrete; (4) slurry circulation and muck removal through a hydraulic transport and separation system; (5) finally carrying out shaft bottom closure followed by machine retrieval [9].

2.1.4. Comparison of downward excavation methods

A comparison of cut-and-cover, diaphragm wall, and VSM is provided in Table 1.

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Table 1. The comparison of three methods

Method	Advantages	Disadvantages	Applicable Scope
Cut-and-Cover	Economical; effective groundwater management with cofferdams	Extended durations; elevated collapse risks in soft soils	Shallow urban tunnels; low-depth excavations
Diaphragm Wall	Sturdy support; proficient arching for deep pits	Intricate setup; joint leakage hazards; increased expenses	Deep shafts in soft soils; subterranean structures
VSM	Automated; adept at high water pressure	High initial technology costs; vulnerable to over-excavation	Deep shafts in urban; high groundwater locales

2.2. Upward excavation methods

2.2.1. Vertical pipe jacking

Vertical pipe jacking is a mechanized shaft construction technique. A typical procedure includes: (1) preparation of a horizontal access tunnel; (2) installation of the vertical jacking system, followed by cutterhead excavation with slurry support to maintain stability; (3) placement of the shaft lining using precast segments; (4) control of grouting pressure together with jacking thrust and bulk pressure to ensure stability. Deformation response in vertical pipe jacking is influenced by multiple interacting factors, which must be considered to predict and control soil deformation [10].

Vertical pipe jacking is a mechanized shaft construction technology. The typical construction process includes: (1) preparation for the horizontal access tunnel; (2) installation of the vertical pipe jacking system, followed by excavation with a cutter head and slurry support to maintain stability; (3) installation of shaft lining using precast segments; (4) ensuring stability by controlling grouting pressure, jacking thrust, and volume pressure. The deformation response in vertical pipe jacking is affected by many interacting factors, which must be considered to soil deformation prediction and control [10].

2.2.2. Upward shield method

Upward shield method is used to construct vertical shafts upward based on existing horizontal tunnels. The typical procedure includes: (1) installing specially designed carbon fiber reinforced polymer reinforced concrete linings inside the tunnel to form a launching opening; (2) deploying a soil pressure balance shield machine equipped with a dome-shaped cutter head and muck conditioning device; (3) conducting upward excavation under controlled face pressure to maintain stability. During construction, ground settlement and tunnel deformation are recorded, and use them to evaluate performance and ensure safety [11,12].

2.2.3. Vertical lift-up method

The vertical lift-up method (also called standpipe) is applied in hydraulic tunnels to construct intake or drainage shafts by sequential upward jacking. The typical procedures include: (1) preparing the launch area with a temporary foundation bed and jacking rails; (2) implementing water-proofing measures and lifting the roof plate upward in stages using hydraulic jacks; (3) connecting the vertical lifting segments using bolts; (4) completing surface works such as riprap protection and intake cap installation [13,14].

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3. The influence of soil deformation induced by vertical shaft construction methods

3.1. Analytical solutions for soil deformation

Analytical solutions provide a theoretical framework for studying soil deformation, using simplified models to measure the effects of loads and friction forces. For downward excavation methods such as cut-and-cover and diaphragm walls, the solutions usually rely on the elastic foundation beam model and arching effect. For instance, the active earth pressure behind the wall can be simplified as:

$$\sigma_h = K_a \gamma h \tag{1}$$

where K_a is the active earth stress coefficient, γ is unit weight of soil, and h is depth, enabling estimates of horizontal displacements and settlements [15,16].

In VSM, Mindlin's solution integrated with stochastic medium theory derives multi-factor formulas, such as vertical:

$$u_z = \left(\frac{\alpha D^2}{4} \right) \left(\frac{1}{r} \right) \tag{2}$$

where α as loss factor, D as diameter, r as radial distance, highlighting settlements peaking at 0.5D from centerline, and modulated by burial depth [10].

Upward methods, including upward shield and vertical lift-up, employ average uniform rigidity ring models for internal forces, e.g., the bending moment:

$$M = \frac{PR^2}{2} (1 - \cos\theta) \tag{3}$$

where P as force, R as ring radius, θ as angle, showing maximum crown dislocations and bolt stresses closing to the ultimate strength [11,14]. Vertical pipe jacking uses limit equilibrium for load models, achieving 90% accuracy in bending moments relative to numerical benchmarks [16].

Relatively, analytical solutions are good at parametric sensitivity (e.g., cohesion over Poisson's ratio) but oversimplify nonlinearities in soft soils, and underestimate collapse risks (10-19% severe failures) compared to numerical methods [17].

3.2. Numerical simulation for soil deformation

Numerical simulations provide dynamic insights to soil deformation, using finite element tools such as Plaxis^{3D}, ABAQUS and Midas GTS NX to model nonlinear situation in complex geology. For the cut-and-cover method, numerical simulations show a continuous increase of horizontal displacements and settlements, with varying differential patterns at different stages [7]. Diaphragm walls simulated using ABAQUS exhibit a parabolic displacement form, verifying the arching effect of load distribution and achieving 90% accuracy in forces. VSM simulations capture the variation and zoning of heave, with settlements being more sensitive than displacements in soft soils [18,19].

Meanwhile for Upward methods, the distinct patterns upward shield FEM analyzes special segments, highlighting arch waist stresses and radial joint shear vulnerabilities from unbalanced deformations [20,21]. Vertical lift-up 3D finite element track analysis of vertical jacking shows joint dislocation (maximum at the crown) and bolt forces, emphasizing jacking control to avoid exceeding the ultimate strength [17]. Simulation using the continuous element method for vertical pipe jacking quantifies the jacking force and evaluates the ranking of influencing factors:

$$F = \pi DLf + Ap \tag{4}$$

where f as side friction, p as end resistance, D as diameter, L as length, A as area, with water content minimally affecting maxima [11,14].

Compared to analytical solutions, simulations do better in handling seismic responses in soil-rock composites, showing displacements at interfaces, but require adjusting against tests [22].

3.3. Scaled model tests for soil deformation

Scale model tests simulate shaft construction to observe deformation mechanisms under controlled conditions, connect theory and field data.

For the downward methods, a 1:30 scale model test of cut-and-cover excavation with four-zone staging limit settlements below 20 mm was adopted, verifying the effectiveness of the cofferdam in groundwater control [6]. Diaphragm wall tests evaluate trench stability, and the results show low noise, but joint leakage enlarges deformation to 0.5D [8]. A 1:30 scale VSM experiment uses PIV to track excavation face instability, identifying a three-stage loading process (growth, slow, and decline) and soil arch evolution, with accelerated rebound after settlement [9,15]. The simplified settlement trough formula in these tests is:

$$S = S_{max} \times \exp\left(\frac{-x^2}{2i^2}\right) \tag{5}$$

where S_{max} is maximum settlement, x is horizontal distance, and i is inflection point distance, aiding prediction of groove-shaped patterns.

Upward shield tests record negligible settlements at 13.5-25.9 m depths by monitor system, confirming pinch valves for pressure stability [23]. And vertical lift-up indoor tests simulate jacking forces, revealing nonlinear increases and minimal water content effects on maxima [17]. Moreover, vertical pipe jacking scale model tests analyze axial responses, showing deformation phases and primary influence on opening rings [11,23]. For heave in upward methods, a basic uplift model is:

$$u_z = \left(\frac{P}{2\pi G}\right)\left(\frac{1-\nu}{r}\right) \tag{6}$$

where P is load, G is shearing modulus, ν is Poisson's ratio, and r is distance, quantifying transitions from convex to concave.

In contrast, compared with analytical solutions, tests are better in visualizing micro-displacements and can capture real-time zoning that is absent in simulations. However, the scale

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effects may overestimate settlement in soft clay. They are less flexible than numerical methods for multi-scenario applications, but can validate models at a lower cost [17].

4. Comparison of different vertical shaft construction methods

4.1. Effects on soil deformation compared by different construction methods

The effects on soil deformation and surroundings are shown in Table 2 and Table 3.

Table 2. The comparison of downward excavation methods

Aspect	Cut-and-Cover	Diaphragm Wall	VSM
Settlement & Lateral	Groove-shaped troughs, S_{max} 0.1-0.3% depth, extending 1.5D; cantilever bulging mid-depth	Parabolic displacements 4-6 mm, settlements 8-11 mm, extending 0.5D due to joints	Heave transition convex-concave 40-70% depth, zoned (arch, transition, cantilever), settlements peak 0.5D
Pore Pressure& Seepage	Dewatering amplifies 30-50% in clays, needs curtains	Minimal changes with bentonite slurry stability	Slurry pressure balances, minimal seepage in soft soils
Structural Interaction	Enclosure stress, differential settlements reducible 19-22% by bracing	Rigid arching, joint shear risks	Lattice heave, fluctuating openings, over-excavation risks

Table 3. The comparison of upward excavation methods

Aspect	Vertical pipe jacking	Upward Shield Tunnelling	Vertical Lift-up
Settlement & Lateral	Heave transition, cantilever	Negligible <1mm	Nonlinear, overburden influence
Pore Pressure & Seepage	Pressurized minimal changes	Grouting stabilization	interface risks
Structural Interaction	Lattice heave, openings	Crown dislocations	Bolt near ultimate, arch openings

4.2. Applicability of different construction methods

The cut-and-cover method induces groove-shaped settlements and cantilever lateral displacements, amplified by dewatering, causing broader surface disruptions [6,14]. It suits shallow to moderate-depth shafts in cohesive soils with good geological conditions.

Diaphragm walls generate parabolic displacements and settlements, with joint leakage extending deformations and minimal noise/vibration [8,15]. This profile fits deep shafts in soft or granular soils with high groundwater, favoring weak karst over strong due to trenching challenges.

The VSM method triggers heave transitions and zoned deformations, minimizing disturbances under pressure [9,18]. It enables urban high-groundwater applications up to moderate depths via automation, but cutter limitations exclude hard rock or unstable karst.

Vertical pipe jacking causes nonlinear jacking forces and deformation phases, influenced by strata, reducing surface impact [10,11]. It suits soft to composite soil-rock with high groundwater in urban corridors, enhanced by grouting, but needs management in seismic zones.

The upward shield method produces negligible settlements but crown dislocations, reducing noise and periods [11,23]. It applies to urban narrow roads and low-rise structures, but instability risks limit use in unstable soils.

The vertical lift-up method leads to crown dislocations and jacking influences from overburden, offering minimal occupation but needing erosion control [13,14]. It fits coastal soft soils in shallow water intake projects for economic benefits, unsuitable for hard strata.

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5. Conclusion

This review systematically compares and analyzes soil deformation mechanisms induced by different vertical shaft construction methods. The main conclusions are as follows:

1. For downward excavation methods, their influence zones are surface-oriented, so the construction would face risks of environmental disturbances. In contrast, mechanized downward methods can generate heave transitions and zoned deformations. The former can induce the instability of risks face and lead to soil failure or collapse finally, and the latter may cause potential risks to surrounding environment such as differential settlement or uplift of adjacent structures.

2. Upward excavation methods yield negligible settlements but facing the increase of crown dislocations and nonlinear force. Overall, downward methods affect broader surface zones due to open excavation, while upward ones minimize surface impact but intensify structural interactions at depth, so in practical construction, the option of different methods should consider multiple parameters.

3. The analytical solutions to solve soil deformation also have some flaws and can be settled. 3D simulation software performs well in continuum analyses but lacks reliable handling of discrete scenarios like joint failures or particle flows, moreover other hybrid models like PFC should serve as supplements for accuracy.

Future construction may focus on combined methods, applying different excavation methods in the same vertical shaft construction to overcome the unavoidable disadvantages by using single method and choose the appropriate construction method for practical projects.

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