

Research on the Characteristics and Quality Control of Sand-Fill Construction in Valley-Type Urban Expansion Areas

Lijun Zhang^{1, a}

¹The Second Geological and Mineral Exploration institute of Gansu Provincial Bureau of Geology and Mineral Exploration and Development, Lanzhou 730020, China

^a1545557162@qq.com

Abstract: To solve the problem of a lack of land resources in the valley-type urban area of Lanzhou and increase space for urban development, sand-filling projects to "level mountains and create land" have been carried out in recent years. However, the poorly graded sand often used in such construction projects has many defects, such as weak particle interlock, poor compaction performance and susceptibility to differential settlement. Consequently, the engineering quality control and evaluation system for these projects urgently requires improvement. This paper studies the construction of the sandy soil filling area in the Gaolan Ecological Restoration and Industrial Development Demonstration Area, Lanzhou. According to laboratory tests (Grain Size Analysis and Heavy Compaction Test) and geophysical exploration (Surface Wave Method, Ground Penetrating Radar), obtain in-situ data such as Standard Penetration Tests, Static Cone Penetrometer Tests, Sand Cone Tests, etc., on parameters related to particle gradation, compaction characteristics, hydraulic properties and other factors influencing compaction efficiency. It shows that there is a quantitative relationship between the degree of fill compaction (λ_c) and in-situ mechanical indicators; for instance, when $\lambda_c \geq 0.88$, $N > 15$ and $P_s > 5$ MPa. Therefore, to obtain a comprehensive understanding of the quality of sandy fill engineering, several types of test data were collected and organised. A Geographical Information System (GIS) has been employed to show the distribution of compaction and indicate high-risk areas. The calculation of the earthwork volume in the demonstration area has achieved a good balance. After process optimisation, the qualified compaction rate ($\lambda_c \geq 88\%$) was over 90%, the characteristic bearing capacity was between 313 and 357 kPa, and thus it met the engineering design requirements. However, the local excavation slope is steeper than the design slope, and therefore a reinforcement measure will be taken. The four modules mentioned above are combined to form a general assessment system for the quality of sandy fill construction sites, and they provide full theoretical support and a technical basis for the quality control, safe operation and maintenance of similar coarse-grained soil fill projects in river valley cities.

Keywords: Sandy soil fill; Quality evaluation; In-situ testing; Compaction degree; Poor gradation; River valley-type urban area.

1. Introduction

With the continuous development of urbanisation in China, the expansion of land resources for valley-type cities has been severely limited by the topography. Lanzhou is a typical valley-belt city, so it is bordered by mountains on both sides in the north and south, and the Yellow River flows through the middle. The terrain is too hilly, so there is little flat land for construction and development, which will harm the city's economic and social progress. To correct the deficiencies mentioned above[1-2], since the early 2000s, Lanzhou has carried out large-scale coarse-grained soil filling projects to "level the peaks and fill the valleys, flatten the mountains to create land". Weathered debris from the surrounding mountains has been used as construction materials, and thus the development space[3-4] of the city has been expanded. Although the large-scale artificial embankments mentioned above have expanded the area of land, many serious geotechnical problems have also arisen, such as uneven settlement of the fill body and slope instability; thus, there are risks to the safety of construction and long-term operation[5-6].

At present, research at home and abroad on "leveling mountains to create land" projects is still in its early stages, and relevant design codes, construction technologies, full-life

quality evaluation systems, etc., have not been systematically developed. Most of the previous research has concentrated on the engineering properties and stability analysis of fine-grained fill materials, such as loess and silty soils. At the same time, there is a shortage of studies on the systematic engineering quality evaluation of poorly graded sandy soil fill sites in arid and semi-arid regions of Northwest China[7]. The filling material has a discontinuous particle gradation and a narrow particle size distribution, so there is poor particle interlock and poor compaction. Therefore, the mechanical response of the fill body will be more complicated, and controlling the uniformity of compaction will be difficult. Therefore, more research needs to be carried out on the material properties, compaction mechanisms and all-round quality evaluation methods of poorly graded sandy soil fill sites to ensure the safety and stability of such projects and prevent disasters such as landslides and differential settlement; at the same time, this will also help to advance the theory of coarse-grained soil fill and provide a reference for urban land development in areas with similar geological and topographical conditions.

Based on the above, the engineering context of this study is the sandy soil fill site in the Gaolan Ecological Restoration and Industrial Development Demonstration Zone in Lanzhou. In order to systematically present the engineering

characteristics and main quality control indicators of poorly graded sandy soil fills, the following several methods will be employed. All kinds of field in-situ tests (Standard Penetration Test, Static Cone Penetrometer Test, Sand Cone Density Test), laboratory geotechnical tests (Grain Size Analysis, Heavy Compaction Test), and geophysical exploration (Surface Wave Method, Ground Penetrating Radar) will be carried out to obtain physical, mechanical and spatial variation information of the fill medium. To study the general correlation between the degree of fill compaction and all sorts of important in-situ mechanical properties, standard penetration test blows per unit length (N) and static cone penetration ratio (Ps) were obtained in this paper. Based on the above, to meet the engineering evaluation requirements, all-weather field tests will be carried out at the fill site. The purpose of the above method is to quickly and non-destructively find out how compacted the land is; it will provide theoretical support and practical data for increasing the engineering reliability and long-term use of land in mountainous and hilly areas across China.

2. Project Overview

2.1. Site Project Introduction

The total planned area of the Gaolan Ecological Restoration and Industrial Development Demonstration Zone (Initial Phase) in the Lanzhou Economic and Technological Development Zone is about 21.49 km². The Construction Land Area is about 7.33 km², and it is next to Angao Highway in the east, North Ring Road to the south (next to Tianfu Shagong Nature Reserve), Xianshuigou in the west, and Xiaoshagou in the north (next to Lianzigou). First, it is one of the first areas for ecological restoration in western China; second, it is a cluster of green innovation and development in Lanzhou; and third, it is a model for integrated urban-industrial development. It is a good plan to expand the urban area and improve the ecological environment for all people.

The experimental site is in Jinsha Village, Shajingyi Sub-district, Anning District, the first development area mentioned above. Block I is bounded by the southern border of the planned area to the south, T1511 Road to the north, Anqin Expressway to the east, and S1502 Road to the west. Block II is bounded by the planned Beishan Expressway in the south, extends north to the area beyond Road B1509, is adjacent to the Anning Connector of the Central Corridor on the east side, and extends west to the area beyond Road S1506. Both blocks are about 6.5 km from the Anning District Government Office, so they are convenient for fieldwork and data collection.



Figure 1. Transportation Location Map of Zone I.



Figure 2. Transportation Location Map of Zone II.

2.2. Technical Approach

Based on in-situ tests, laboratory experiments, engineering geophysical data, etc., regression analysis was carried out on the degree of compaction, standard penetration test (SPT) blows per unit weight, static cone penetration resistance and surface wave shear wave velocity at different depths to obtain quantitative relationship models among these indices. Based on the above, a general evaluation method for the engineering quality of thick sand fill sites has been developed.

2.3. Site Conditions Analysis

The area of the study is at the junction of the Longxi Loess Plateau and the Qinghai-Tibet Plateau. Tectonically, it is a compound intersection of the Qilu-Helan Mountain zigzag structural system and the Wuwei-Lanzhou structural belt of the Hexi System, so it has a complex tectonic pattern and active neotectonic movement (see Figure 3).

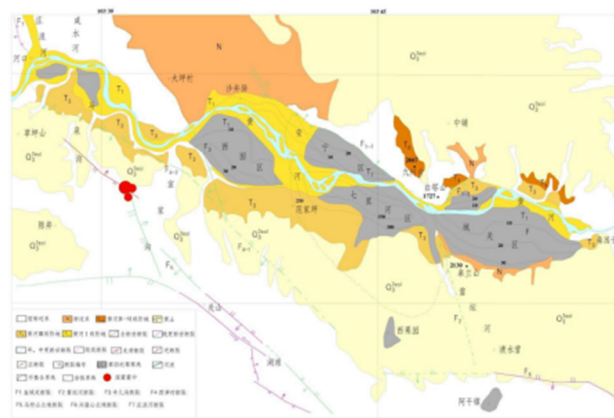


Figure 3. Geological Structure Distribution Map of the Study Area.

The three main tectonic blocks in this area are: The Limashagou Syncline is about 25 km long and 10 km wide, extending from Hajiaju to Shajingyi, and its axis is NNW. The main part is composed of Neogene strata with dip angles of 7°-15°, and the Jinchengguan thrust fault on the north bank of the Yellow River is about 25 km long. The early-to-middle Pleistocene fault will not be in the construction area. The length of the Jiangou non-seismic faults is more than 20 km.

According to seismic zoning, the study area is in the Tianshui-Lanzhou-Hexi Corridor seismic belt. According to the relevant code, the site seismic fortification intensity is VIII, the design basic seismic acceleration is 0.20g, and the response spectrum characteristic period is 0.45s. Figure 4 is a diagram of the seismic tectonics and seismic hazard in the

study area.

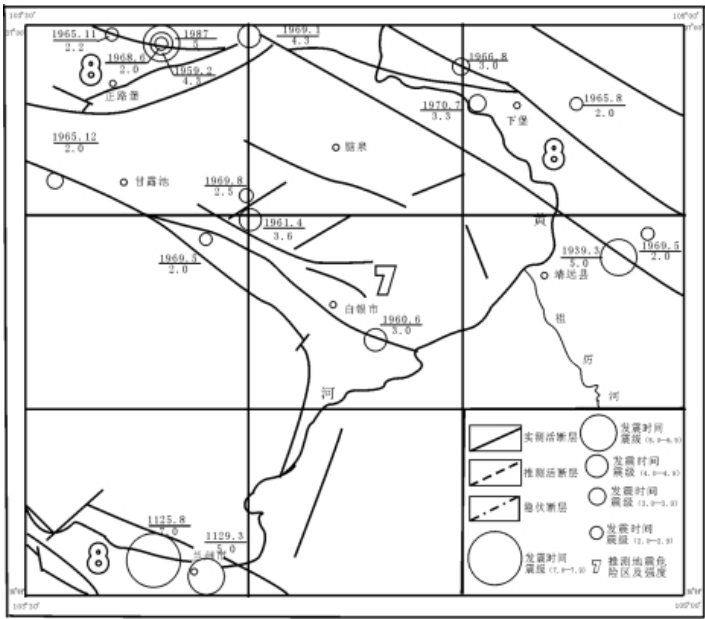


Figure 4. Seismic Structure and Seismic Hazard Zoning Map of the Study Area.

The stratigraphy and lithology at the site can be divided into two parts from top to bottom: ① Layer (Q4ml) is artificial fill material in the embankment area. It is a reddish-brown colour, slightly damp, and either loose or firm. ① The main constituents are weathered sandstone clasts and silt. ② Layer (N): The whole area is strongly weathered sandstone. It is reddish-brown in colour, has a medium to fine-grained structure, is mud-calcareous cemented, and easily fractures. The two basic parts of the hydrogeological environment are pore-fracture water in clastic rocks (which is in Neogene sandstones and has a low water yield) and pore water in loose

rocks (river valley groundwater). According to the survey, there is no stable groundwater in the fill area.

Preliminary analysis of the composite core logs from boreholes in all areas shows that there are correlations among the indicators of Standard Penetration Test (SPT), Cone Penetrometer Test (CPT), and in-situ density test. Based on the test results at the same location and depth in Block II, it was found that when the compaction degree $\lambda \geq 0.88$, the measured hammer blows in the SPT exceeded 15, and the static cone penetration resistance ratio exceeded 5 MPa (see Table 1).

Table 1. Comparison of Fill Evaluation Indicators in Area II.

Compaction Degree	Loose	Slightly Dense	Medium	Compact
In-situ density test (Compaction degree λ_c)	$\lambda_c < 0.84$	$0.84 \leq \lambda_c < 0.88$	$0.88 \leq \lambda_c < 0.91$	$\lambda_c \geq 0.91$
Standard Penetration Test (Actual number of blows N)	$N \leq 10$	$10 < N \leq 15$	$15 < N \leq 30$	$N > 30$
Static cone penetration test (Specific Penetration Resistance Ps/MPa)	$PS \leq 3$	$3 < PS \leq 5$	$5 < PS \leq 9$	$PS > 9$

3. Analysis of Engineering Characteristics of Sandy Soil Fill Sites

3.1. Influence of Physical and Mechanical Properties of Sand Soil on Embankment Quality

3.1.1. Particle Gradation Characteristics

The particle size distribution of laboratory blocks I and II

(a total of 21 test samples) is presented in Table 2. According to the Standard Test Methods for Soil (GB/T 50123-2019), both blocks of sandy soil have a poor gradation index ($C_u < 5$, $1 \leq C_c \leq 3$) and weak particle interlock. Additives are to be added.

Table 2. Statistical Summary of Sand Soil Particle Analysis Results.

Area Name	Stratum	Number of Samples	d60(mm)	d30(mm)	d10(mm)	Cu	Cc
Block I	Artificial Fill	15	0.691–0.767 (0.740)	0.470–0.571 (0.536)	0.238–0.297 (0.267)	2.50–3.22 (2.78)	1.20–1.71 (1.46)
	Coarse Sand	6	0.715–0.760 (0.721)	0.460–0.552 (0.522)	0.237–0.267 (0.251)	2.73–2.97 (2.87)	1.43–1.75 (1.51)
Block II	Artificial Fill Soil	58	0.326–0.649 (0.456)	0.175–0.431 (0.295)	0.100–0.236 (0.157)	2.04–3.94 (2.94)	0.78–1.59 (1.23)

Note: Values in parentheses indicate averages.

3.1.2. Compaction Characteristics and Hydraulic Properties

Block I: 154 samples were obtained from the 26 boreholes, and three sets of test specimens for heavy compaction tests were prepared. Block II has a total of 318 filling samples from 53 boreholes and 22 sets of test specimens have been prepared. Table 3 is the corresponding maximum dry density and

optimum moisture content data.

Based on the results of the compaction test, the mean maximum dry density of Block I is 1.92 g/cm³ and the mean optimum moisture content is 7.6%; Block II has corresponding values of 1.96-1.99 g/cm³ and 2.9%-5.2%. The moisture in the field should be low enough to avoid "rubber soil" and slope failure.

Table 3. Statistical Summary of Heavy Compaction Tests.

Area Name	Item	Sample Count	Maximum	Minimum
Block I	Optimal Moisture Content (%)	3	7.8	7.5
	Maximum Dry Density (g/cm ³)	3	1.93	1.92
Block II	Optimum Water Content (%)	22	2.9	5.2
	Maximum Dry Density (g/cm ³)	22	1.96	1.99

3.2. Construction Techniques and Quality Control Problems in Fill Construction

3.2.1. Layered Fill Placement and Compaction Parameters

A 22-ton vibratory roller (excitation force 350 kN) was employed at the construction site, the thickness of the controlled loose layer was 25-30 cm, and the compaction speed was 2.5-4 km/h. However, because of the high fluidity of coarse sand, the compaction efficiency of loose layers deeper than 30cm was reduced by 4-6% (Spearman's coefficient of correlation: 0.68). Therefore, there should be a relatively thin soil layer.

3.2.2. Moisture Content Control and Improvement Measures

To solve the problem of the low moisture content in coarse sand (8%-12%), an intelligent sprinkler system with a control accuracy of $\pm 1\%$ was introduced to raise it to 10%-14% and reduce water consumption by about 30%. For poorly graded

areas, 3% of clay (by mass) was added to increase the coefficient of uniformity (C_u) to 5.2 and raise the compaction compliance rate by about 15%.

4. Development of a Quality Evaluation System for Sandy Soil Fill Sites

4.1. Selection of Evaluation Indicators and Weights

4.1.1. Core Indicator System

The three levels of the index system for the quality of sandy soil fill projects are shown in Table 4. Criteria for Level: Physical Indicators (Degree of Compaction, Moisture Content), Mechanical Indicators (SPT N-value, Static Cone Penetration PS value, Bearing Capacity), Stability Indicators (Slope Gradient). Index Level: 12 particular items. Among them, the weight of compaction (0.35), slope gradient (0.25) and bearing capacity (0.20) are the main controlling factors.

Table 4. Evaluation Indicators and Weights for Sand Fill Engineering Quality (AHP Method).

Objective Layer	Criterion Layer (Weight)	Indicator Layer (Weight)	Description
Quality of Sand Fill Construction	Physical Indicators (0.35)	Compaction Degree (0.35)	Sand-injection test, $\lambda_c \geq 88\%$
		Moisture Content (0.00)	Controlled within $\pm 2\%$
	Mechanical Properties (0.40)	Standard Penetration Test N Value (0.15)	① Layer average 23.1 blows
		Static penetration PS value (0.10)	Weighted average 6.55-7.79 MPa
		Bearing Capacity (0.20)	Static probe calculation 313-357 kPa
	Stability index (0.25)	Slope Gradient (0.25)	Fill 1:1.5, Cut 1:1.5

4.1.2. Weight Determination

Based on the opinions of the five experts in geological engineering, the AHP was used. Consistency check of the judgment matrix showed $CR < 0.1$, so the weights are reasonable.

4.2. Combination of Several Appraisal Methods

4.2.1. Coupling of In-Situ Testing Methods

Standard Penetration Test: ① Artificial fill layer $N=4-98$ blows (average 23.1 blows), density: loose-dense (dense points 26.9%, medium-dense 47.1%). Layer ② coarse sand: $N=5-38$ blows (mean 22.1 blows), slightly dense to medium dense.

Static Cone Penetration Test: $PS = 3.50-21.35$ MPa (Weighted Mean 6.55-7.79 MPa). According to the formula

$f_{ak}=36PS+76.6$ for medium-coarse sand, the bearing capacity is 313-357 kPa; it meets the requirement of industrial land (≥ 200 kPa).

Sand-injection test: 112 of the 124 points met the $\lambda_c \geq 88\%$ (compliance rate of 90.32%) before correction. All 30 items have been corrected and meet the requirements (100% compliance). The Compaction Stability at -3.6m was relatively good (Coefficient of Variation = 0.02).

4.2.2. Spatial Visualization Evaluation

GIS-based contour maps of compaction at the -0.6m to -3.6m level show that compaction is higher in the lower parts, and the coverage of $\lambda_c \geq 90\%$ at the -3.6m level is 85%. The degree of compaction near the original saline-water ditch on the west side is relatively low (82%-86% before remediation), so it must be dealt with separately.

5. Empirical Analysis of Engineering Quality Evaluation (Block I as an example)

5.1. Assessment of Current Quality Status

5.1.1. Earthwork Volume Verification

Verification of Calculations with the Two Grid Specifications:

10m × 10m grid: The calculated fill volume is 398,230.07 m³ (after deducting 184,056 m³ for Road S1502 and adding 3,042.33 m³ from the northern area), and the excavation volume is 310,625.80 m³.

20m × 20m grid: The calculated fill volume is 310,625.80 m³ and the excavation volume is 292,304.36 m³.

The relative difference of the two calculation methods is less than 4%, and therefore it meets the accuracy requirements in the "Urban Surveying Specifications" (CJJ/T 8-2011).

5.1.2. Compaction Degree and Bearing Capacity

The results of the compaction degree test for the typical depth layer are as follows: At the -0.6m level, λ_c was between 86% and 93% (mean = 89.2%). At the -3.6 m level, λ_c was between 88% and 94% (mean = 91.5%). The density of all layers has met the design requirements after the correction work. Out of the 22 locations for the static cone penetration test, 19 (86.4%) had estimated characteristic values for the foundation bearing capacity of no less than 300 kPa and were therefore suitable for the construction requirements to be met.

Table 5. Compaction Degree Statistics of Each Layer in Block I After Remediation.

Layer (m)	Number of Test Points	λ_c Range (%)	Average (%)	Pass Rate (%)
-0.6	30	88~93	89.2	100
-1.2	30	88~94	89.8	100
-1.8	30	89~94	90.5	100
-2.4	30	89~94	90.8	100
-3.0	30	90~94	91.2	100
-3.6	30	88~94	91.5	100

5.1.3. Slope Stability Verification

The height of the upper slope is 1.28 - 4.09m, and the actual slope ratios are 1:3.5 - 1:2. Although it is steeper than the Design Slope Ratio of 1:1.5, it is still temporarily stable. The cut slope heights are from 34.56m to 39.60m, the actual slopes are 1:0.82 to 1:0.18, and they are steeper than the design slope (1:1.5). Their calculated stability factors range from 1.05 to 1.15, below the minimum safety factor specified in standards (≥ 1.25), necessitating reinforcement measures.

5.2. Reasons for Quality Problems

The excavation speed is too high for the cut slope; as the "layered excavation and timely support" method has not been employed, the temporary slope is too steep. Insufficient Control of Compaction Parameters: The actual thickness of the loose layer in the west exceeded the 30 cm control requirement and reached 35-40 cm; thus, the compaction in this area was only 82%-86%. Poor gradation of the fill sand material: The uniformity coefficient $C_u < 5$, so there is weak interlock among the particles and uneven compaction. Presence of strongly weathered sandstone blocks in the fill material: At intermediate depths of boreholes ZK01 and ZK05, the standard penetration test (SPT) blow count N value was more than 30 blows (with a maximum of 98 blows), and it was found that hard interlayers cause abnormal compaction in these areas.

6. Quality Improvement Measures and Optimization Recommendations

To address the problems in quality that have occurred, optimisation of the construction process will be carried out as follows: For excavation slopes, a combined "shotcrete anchoring and drainage ditch" scheme will be employed, and the main parameters are an anchor rod length of 4-6m and a shotcrete thickness of 10cm. The reinforcement of the embankment shall be geogrids with a tensile strength of $\geq 50 \text{ kN/m}$. At the time of compaction, a real-time monitoring system (accuracy $\pm 1\%$) must be employed;

strictly control the layer thickness (about 30 cm) and the number of rolling passes (6-8 times), and carry out compaction density tests immediately after rolling. The extended monitoring system will cover all times during the construction of the project; every 7 days, GNSS slope movement measurements (accuracy of $\pm 3\text{mm}$) will be taken, and once a month, spot checks of compaction density will be carried out. Monitor the quarterly settlement of the operational InSAR technology, and the settlement rate should be less than 3 mm per month. At the same time, a three-level early warning system based on the cumulative displacement in a month ($>5\text{mm/month}/10\text{mm/month}/15\text{mm/month}$) has also been established. All of the above are to constitute the all-weather technical system of the project.

7. Conclusions

(1) Studies on the Gaolan Block I in Lanzhou indicate that both its core fill layers (① artificial fill and ② coarse sand) exhibit poor gradation characteristics (unevenness coefficient $C_u < 5$). Compaction test results show a maximum dry density of approximately 1.92 g/cm^3 and an optimum moisture content of about 7.6%. To meet engineering requirements, the fill sand must be improved by adding clay or other modifying materials.

(2) Following construction remediation, the compaction degree λ_c of all soil layers reached no less than 88%, with characteristic bearing capacities ranging from 313 to 357 kPa, meeting relevant engineering technical specifications. The measured slope ratios (1:0.82 to 1:0.18) of the excavated slopes in this block exceeded the design allowable values. Engineering measures such as shotcrete anchoring support must be implemented to ensure stability. A multi-method evaluation system combining Standard Penetration Tests (SPT), Static Cone Penetration Tests (SCPT), and the Sand Cone Test can effectively assess the quality of fill embankments. Integrating spatial analysis techniques from Geographic Information Systems (GIS) enables precise identification and localization of areas with compromised engineering quality.

(3) This study established a three-dimensional evaluation index system encompassing "physical properties—mechanical properties-stability," highlighting the characteristics of sandy soil embankment projects in arid regions. By integrating intelligent moisture content control technology with real-time compaction monitoring technology, the precision and efficiency of construction process control were enhanced. Based on multi-level field data, GIS generated spatial distribution contour maps of compaction degree, enabling visual representation of engineering quality and identification of vulnerable zones, thereby providing technical support for dynamic quality control.

The other is that it has not studied the long-term stability of sandy soil under freeze-thaw cycles. Given that the maximum frost depth in the demonstration area is 1.03m, there will be considerable freeze-thaw damage caused by frost penetration. In the future, the range of the freeze-thaw cycle test will be extended to $-15^{\circ}\text{C} \sim 25^{\circ}\text{C}$, we will systematically study the pattern of compaction decay, and explore the application of digital twin technology to build a dynamic quality-control platform for all periods in the life cycle of embankment projects.

References

- [1] Xue, Q. (2024). Discussion on the new path of spatial development direction of river valley city under the new situation: a case study of Lanzhou urban area. *Chinese & Overseas Architecture*, 5, 50–55.
- [2] He, S., Wang, X., Dong, J., et al. (2019). Three-dimensional urban expansion analysis of valley-type cities: a case study of Chengguan District, Lanzhou, China. *Sustainability*, 11(20), 5663. <https://doi.org/10.3390/su11205663>
- [3] Nie, Q. F., Bao, J. R., Chen, W. M., et al. (2022). Mapping the dynamics of urban land creation from hilltop removing and gully filling projects in the river-valley city of Lanzhou, China. *Journal of the Indian Society of Remote Sensing*, 50(10), 1813–1826. <https://doi.org/10.1007/s12524-022-01567-9>
- [4] Fan, Z., Xu, J., & Xie, Y. (2002). A study on sustainable land use in fringe area of valley city Lanzhou. *Journal of Arid Land Resources and Environment*, 2, 95–101.
- [5] Zhang, M., Tan, X., Dong, Y., et al. (2019). Initial analysis on environmental effect of cutting hills to backfill ditch project on Loess Plateau—Take Yan'an New District as an example. *Geological Review*, 65(6), 1409–1421.
- [6] Yan, B. (2020). Potential hazard assessment of dam failure mudflow in land creation projects in the Lanzhou [Master's thesis]. Lanzhou University.
- [7] Zhu, F. C., Yang, Z. J., Wang, J, et al. (2025). A numerical simulation of compaction of poorly graded silty fine sand roadbeds. *Journal of Hunan University of Technology*, 39(1), 1–8.
- [8] Dai, J., & Yuan, D. (2002). Principal features of the active tectonics in Lanzhou area. *Plateau Earthquake Research*, 3, 35–40.