

Development Characteristics of Expansive Soils along the Handan Section (Hebei Province, China) of the Middle Route of the South-to-North Water Diversion Project and Their Influence on Slope Stability

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**Development Characteristics of Expansive Soils along the Handan Section
(Hebei Province, China) of the Middle Route of the South-to-North Water
Diversion Project and Their Influence on Slope Stability**

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Abstract Expansive soils threaten water-transfer canals through moisture-sensitive deformation and strength loss, but material tests alone do not establish where rainfall will reach vulnerable slope layers. This study integrates geological investigation, 405 sets of physical and swelling–shrinkage tests, direct-shear testing and variably saturated seepage modelling for the Handan section (Hebei Province, China) of the Middle Route of the South-to-North Water Diversion Project. Expansive soils (rocks) extend approximately 50 km along the canal and cover about 220 km². They comprise Neogene lacustrine claystone, Lower Pleistocene lacustrine clay and clay weathered from claystone, with buried occurrences considerably more extensive than surface exposures. Moderately and weakly expansive materials dominate, and the sampled occurrences concentrate at elevations of 70–90 m. Mineralogical and swelling tests identify moisture-sensitive materials, while compression and repeated direct-shear tests demonstrate wetting-induced weakening. Peak cohesion decreases from 146.9 to 37.1 kPa between gravimetric water contents of 20% and 25%, indicating a sensitive interval for the tested soil. The seepage scenarios explain how this susceptibility may be

activated: 7 m deep fractures connect rainfall to the potential slip zone, where a front-fracture monitoring point reaches saturation after approximately 100 h at 3 mm/h, compared with about 250 h at 1 mm/h. Saturation remains spatially incomplete, and fracture location redistributes the wetting response. The combined evidence supports a mechanism linking material susceptibility, preferential infiltration and localized weakening, rather than a prediction of failure time. This framework can inform assessment of comparable fissured clay canal slopes, subject to site-specific hydraulic calibration and mechanical verification.

Keywords Expansive soil · South-to-North Water Diversion Project · Development characteristics · Engineering geological properties · Rainfall infiltration · Slope stability

1 Introduction

Expansive soils contain moisture-sensitive clay minerals, particularly smectite, and may swell during wetting, shrink during drying and lose strength as their hydraulic state changes. These processes affect canals, foundations and transport earthworks in different geological and climatic settings. Research on smectite-rich Ankara clay in Turkey demonstrates the importance of fabric-dependent swelling, while monitoring and laboratory studies of British clay slopes identify seasonal moisture change and weather-driven deterioration as persistent engineering concerns (Avsar et al. 2009; Smethurst et al. 2012; Stirling et al. 2021). The international problem is therefore not simply the presence of expansive minerals, but how material susceptibility interacts with field-scale water pathways and engineering exposure.

International research provides complementary explanations at material and slope scales. The unsaturated-strength framework of Fredlund et al. (1978) distinguishes the contributions of stress and matric suction, while Alonso et al. (1999) relate expansive-clay behaviour to interacting structural levels. Suction-controlled wetting–drying tests demonstrate that hydraulic history affects deformation and mechanical response (Nowamooz and Masrouri 2008); swelling measurements on Ankara clay and highly expansive Handan clay additionally show why fabric, density and initial water content must be considered when interpreting swelling indices (A

vsar et al. 2009; Liu et al. 2019). Reviews of desiccation cracking describe the roles of moisture loss, shrinkage, boundary restraint and crack-network development, and identify unresolved issues in linking laboratory observations to numerical representations (Shi et al. 2014; Tang et al. 2021; Al-Jeznawi et al. 2025). At the hydraulic scale, Li et al. (2011) explicitly distinguish the crack network from the soil matrix when describing water retention and permeability. Instrumented expansive-soil slopes show that rainfall response involves fissures, suction changes and delayed deformation (Ng et al. 2003; Zhan et al. 2007). Longer-term observations in London Clay and studies of embankment deterioration extend this perspective to seasonal moisture cycling and progressive changes in earthwork performance (Smet hurst et al. 2012; Stirling et al. 2021). Together, these studies establish the need to connect laboratory evidence of moisture sensitivity with the geometry and timing of water entry, rather than treating swelling tests and infiltration calculations as separate explanations of slope behaviour.

The remaining issue addressed here is how to connect regional geological heterogeneity, laboratory evidence of wetting-induced weakening and fracture-controlled infiltration within one canal-slope assessment. This is relevant to excavated clay slopes where a low-permeability matrix coexists with preferential flow paths, although the controlling parameters vary between sites. The Handan section provides a case involving lacustrine expansive clay and claystone, widespread buried occurrences and deep excavation. The uppermost 1.5–2.0 m of the slopes consists of artificial replacement fill over moderately to strongly expansive material; intense rainfall in southern Hebei on July 19, 2016, induced localized failures. These conditions motivate investigation of whether fractures can transmit rainfall through the cover to susceptible underlying layers. Regional tectonic conditions form part of the geological setting, but earthquake-induced fracture generation is not simulated in this study.

This study integrates field mapping, hand-auger exploration, manual test pits and drilling with laboratory testing and seepage modelling to (i) delineate genetic types and spatial exposure of expansive soils (rocks), (ii) characterize their composition,

swelling–shrinkage behaviour and moisture-dependent strength, and (iii) compare rainfall infiltration in unfractured and 7 m deep fractured slope scenarios. The laboratory results establish susceptibility to wetting; the model examines the locations and timing of wetting that could activate this susceptibility. Their integration supports a process-based interpretation of canal-slope hazards and identifies conditions under which the mechanism may be relevant elsewhere. It does not constitute a calibrated prediction of slope failure or a fully coupled stability calculation.

2 Regional Geological Setting

The Handan section of the main canal of the Middle Route of the South-to-North Water Diversion Project is 80 km long. It crosses the Zhang River from Fengle Town, Anyang, Henan Province, enters Handan, and leaves Handan north of Dengshang Village, Yongnian County, before entering Xingtai. The canal section lies in the transitional zone from the eastern foot of the Taihang Mountains to the Hebei Plain, with an overall topographic gradient from west to east and widespread ridge-like uplands along the route. Groundwater occurs mainly as pore groundwater and fissure groundwater, hosted in sandy interbeds and fractures within expansive soils (rocks), respectively. Aquifers are mostly lenticular and poorly continuous, with high clay contents, low permeability ($k < 10^{-4}$ cm/s), and limited water yield. The area is dry in winter and spring and experiences intense rainfall in summer, and river stages are characterized by rapid rises and falls.

The Handan canal section is located within the North China seismic region and adjacent to the Hebei Plain seismic belt, where regional tectonic activity is relatively strong. Several moderate-to-strong earthquakes occurred in the Handan, Xingtai, and Cixian areas during the 1960s. Major concealed faults near the canal section include the Xingtai-Handan fault segment, the Cixian-Daming fault segment, and the Zidongshan fault. The Handan potential M6.5 seismic source zone contains Qp₃ active faults; the Xingtai-Handan fault is dominated by strike-slip creep, and the central segment of the Cixian-Daming fault has remained active in recent years. A magnitude 3.6 earthquake occurred in Linzhang on April 21, 2019. According to the Report on Zonation of Design Ground-Motion Parameters along the Middle Route of the South-

to-North Water Diversion Project, the peak ground acceleration for this canal section is 0.15 g and the basic seismic intensity is VII.

3 Development Characteristics of Expansive Soils

3.1 Genesis of Expansive Soils

The Handan canal section is located on the eastern margin of the Taihang Mountain uplift. Since the Neogene, a warm and humid depositional environment dominated by oxidation has produced a very thick lacustrine terrigenous clastic succession, including thick-bedded purplish-red claystone and sandstone lenses. Claystone rich in clay minerals constitutes the parent material of the expansive soils (rocks) in this region. Weathering has transformed it into brownish-red and brownish-yellow expansive clay with grayish-green mottling, as well as variegated expansive clay; the differences in color reflect variations in sediment composition and depositional environment.

Since the Quaternary, the climate has alternated between warm and cold and between dry and humid conditions. During the Lower Pleistocene (Qp₁), glacial-interglacial processes caused surface runoff and glacial meltwater to transport clay-rich material into depressions, forming Lower Pleistocene expansive clay. A typical example is the grayish-green expansive clay containing sandy lenses along the western margin of the Yongnian Depression, which formed mainly in standing-water or slow-flowing-water environments under cold climatic conditions. According to genesis, the expansive soils (rocks) along the Handan canal section can be divided into three types: Neogene lacustrine expansive claystone, Quaternary Lower Pleistocene lacustrine clay, and expansive clay formed by weathering of claystone.

3.2 Development and Distribution Characteristics of Expansive Soils

(1) Distribution range

A special investigation covering 450 km² along the Handan section, integrating geological mapping, engineering drilling, manual test pits, in situ testing, and sampling tests, delineated the expansive soils (rocks) as being mainly distributed west of the Beijing-Guangzhou Railway, extending approximately 50 km along the canal and covering a total area of about 220 km² (Fig. 1). According to surface exposure and burial conditions, they can be classified into surface-exposed and buried types.



Fig. 1 Distribution of expansive soils (rocks) along the Handan section of the Middle Route of the South-to-North Water Diversion Project

(i) Surface-exposed type

According to exposed lithology and stratigraphic age, the surface-exposed type includes two categories: Qp_1 clay expansive soil and N_1 claystone containing sandstone lenses as expansive rock.

Qp_1 expansive clay is mainly distributed in the southwestern part of Jiehedian Township, Yongnian, and from Sanling Township to Huangliangmeng Town, covering approximately 13.1 km^2 and extending about 2.1 km along the canal. It is predominantly brownish-yellow to yellowish-brown, with minor grayish-green mottling and calcareous nodules. The soil is dense, with well-developed large and persistent fractures that are commonly filled with grayish-green claystone bands; local

iron-manganese staining is also present.

N_1 expansive claystone containing sandstone lenses is mainly distributed from Dong'erzhuang Village to Xiazhuang Village in Handan, covering approximately 1.8 km² and extending about 1.3 km along the canal. The lithology consists of variegated brownish-yellow to brownish-red claystone, locally intercalated with feldspathic and quartz sandstone lenses, and contains minor grayish-green mottling, calcareous nodules, and iron-manganese staining. The claystone is dense and contains well-developed microfractures.

(ii) Buried type

According to the lithology and age of the overburden, the buried type can be divided into four categories: N_1 expansive claystone beneath Qh loam; N_1 expansive claystone beneath Qp₃ loess-like soil; Qp₁ expansive clay and N_1 expansive claystone beneath Qp₃ loess-like soil; and N_1 expansive claystone beneath a Qp₁ muddy gravel-sand layer.

N_1 expansive claystone beneath Qh loam is mainly distributed along the Huangliangmeng-Jiehedian-Yonghehui corridor in Yongnian, in the southeastern part of Hucun Town in Handan, and in Guanglu Town, Cixian, covering a total area of approximately 32.4 km² and extending about 7.2 km along the canal. The surface Qh loam is 1.0–12.5 m thick. The underlying N_1 claystone is brownish-yellow and dense, with relatively well-developed long persistent fractures that are commonly filled with grayish-green clay bands; local iron-manganese staining is present.

N_1 expansive claystone beneath Qp₃ loess-like soil is mainly distributed from Xiazhuang Village through Nancheng Township to Lintan Town, as well as northwest of Jiehedian Township and southwest of Guanglu Town, covering a total area of approximately 90.6 km² and extending about 14.5 km along the canal. The surface Qp₃ loess-like soil is 0–8.7 m thick and exhibits moderate to slight collapsibility. The underlying N_1 claystone is grayish-green or brownish-yellow and dense, with extremely well-developed microfractures and small fractures that are commonly filled with grayish-white or grayish-green clay; local iron-manganese staining is also observed.

Qp₁ expansive clay and N_1 expansive claystone beneath Qp₃ loess-like soil are

mainly distributed in the northwestern and southwestern parts of Sanling Township, Yongnian, covering a total area of approximately 16.9 km² and extending about 6.05 km along the canal. The surface Qp₃ loess-like soil is 1.0–6.8 m thick and is slightly collapsible. The Qp₁ clay is mostly brownish-red or variegated, with locally developed long persistent fractures whose surfaces contain grayish-white clay or calcareous fillings. The N₁ claystone is brownish-yellow to brownish-red, with grayish-green mottling and calcareous nodules, and contains well-developed microfractures.

N₁ expansive claystone beneath a Qp₁ muddy gravel-sand layer is mainly distributed from southeast of Xinpo Town to Guanglu Town and the southeastern part of Dayu Town in Cixian, covering a total area of approximately 65.2 km² and extending about 4.2 km along the canal. The surface Qp₁ muddy gravel-sand layer is variegated, contains more than 55% gravel with particle sizes of 20–60 mm, and is 0.6–12.8 m thick. The underlying N₁ claystone is grayish-green to brownish-yellow, with banded rust staining, spotted manganese staining, and minor calcareous concretions, and is relatively well cemented.

(2) Classification of swelling grades

According to swelling potential, the expansive soils (rocks) in the study area are classified into strong (Grade I, $\delta_{ef} \geq 90\%$), moderate (Grade II, $65\% \leq \delta_{ef} < 90\%$), and weak (Grade III, $40\% \leq \delta_{ef} < 65\%$) categories. Strongly expansive soils (rocks) are mainly distributed in ridge-like uplands from Lintan Town, Cixian, to Yinbao Village, Taicheng Township, covering approximately 10.93 km². Moderately expansive soils (rocks) are the most widely distributed, covering approximately 119.07 km² across multiple geomorphic units. Weakly expansive soils are mainly distributed east of the canal in Hucun Town, Taicheng Township, Guanglu Town, and Lucunying Township, with scattered occurrences in western Xinpo Town, covering approximately 90.00 km² (Fig. 2).

Using the group counts in Table 1, the 381 samples comprise 22 strongly, 149 moderately and 210 weakly expansive groups, corresponding to 5.8%, 39.1% and 55.1%, respectively. Within each swelling grade, 81.8%, 77.9% and 78.1% of the samples, respectively, occur at elevations of 70–90 m. Strongly expansive samples are

absent below 70 m; the two samples below 50 m are weakly expansive. These sample-frequency statistics should be distinguished from the mapped areas of the swelling grades, because the sampling distribution is not an area-weighted estimate. The concentration at 70–90 m identifies an interval warranting attention where canal excavation intersects the expansive strata.



Fig. 2 Distribution of expansive soils (rocks) of different swelling grades along the Handan section of the Middle Route of the South-to-North Water Diversion Project

Table 1 Statistics of swelling potential of expansive soils at different elevations (381 groups)

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>90	4	18.2	14.8	6	4.0	22.2	17	8.1	63.0
80–90	11	50.0	8.0	51	34. 2	37.2	75	35.7	54.7
70–80	7	31.8	4.3	65	43. 6	40.4	89	42.4	55.3
60–70	/	/	/	24	16. 1	50.0	24	11.4	50.0
50–60	/	/	/	3	2.0	50.0	3	1.4	50.0
<50	/	/	/	/	/	/	2	1.0	100.0

4 Engineering Geological Characteristics of Expansive Soils

4.1 Material Composition of Expansive Soils

(1) Particle-size composition of expansive soils

Expansive soils along the Handan canal section are dominated by fine particles (Table 2). The fraction finer than 0.005 mm ranges from 35.5% to 46.0%, while the fraction finer than 0.002 mm ranges from 16.3% to 21.2%. The former is termed the clay-size fraction in the source investigation; the latter corresponds to the <0.002 mm clay-size boundary commonly used in international soil descriptions. These fractions overlap and should not be added. Lacustrine samples contain more fine material than the weathered-claystone sample, indicating a genetic influence on texture. Mineral identity is evaluated separately in Table 3 rather than inferred from particle size alone.

Table 2 Particle-size composition of different types of expansive soils along the Handan canal section

Genetic type	Lithology	Mean particle-size content (%)			
		>0.05 (mm)	0.05– 0.005 (mm)	<0.005 (mm)	<0.002 (mm)
Claystone weathering	Brownish red	22.7	41.8	35.5	16.3
Lacustrine deposition	Grayish green	17.6	36.4	46.0	21.2
	Grayish green-grayish white	18.5	40.6	40.9	19.2

(2) Mineral composition of expansive soils

The minerals in expansive soils comprise detrital and clay minerals (Table 3).

Quartz, calcite and feldspar constitute the principal non-clay components, whereas clay-mineral composition provides the main basis for interpreting swelling susceptibility. Arithmetic means for the 12 listed samples give quartz and calcite contents of 25.7% and 18.2%, respectively. Quartz reaches 40% in the brownish-red soil at Yiquan, Cixian; calcite reaches 60% in sample 11 from north of Nancheng, Handan. This variability indicates that moisture-sensitive clay minerals occur within markedly different mineral assemblages along the canal.

Table 3 Mineral composition of typical expansive soils (rocks) in the Handan section

Number	Lithology name	Sampling site	Detrital minerals (%)			Clay minerals (%)			
			Quartz	Calcite	Feldspar	Smectite	Illite	Kaolinite	Chlorite
1	grayish-white expansive soil	Xiguanzhuang Village, Sanling Township	15	25	0	18	15	21	6
2	reddish-brown expansive soil	Yiquan, Cixian	40	3	2	41.3	5.5	8.3	0
3	grayish-green expansive soil	South of Nancheng, Handan	35	7	2	33.6	11.2	7.3	3.9
4	reddish-brown expansive soil	North of Nancheng, Handan	25	30	2	17.2	6.5	15.1	4.3
5	reddish-brown expansive soil	Donghuaishu, Cixian	26	5	15	34	10	10	0
6	grayish-green expansive soil	Qicun, Handan	28	20	0	32	8	12	0
7	grayish-green expansive soil	Caozhuang, Handan	30	0	3	57.6	4.7	4.7	0
8	grayish-green expansive soil	Nanxiazhuang, Handan	16	31	0	30	10	7	6
9	grayish-green expansive soil	Xixiazhuang, Handan	28	30	0	27.3	4.2	6.3	4.2
10	grayish-green expansive soil	Chengang Village, Hanshan District	30	1	6	54.2	3.8	5	0
11	reddish-brown expansive soil	North of Nancheng, Handan	10	60	3	14.9	6.8	5.4	0

Number	Lithology name	Sampling site	Detrital minerals (%)			Clay minerals (%)			
			Quartz	Calcite	Feldspar	Smectite	Illite	Kaolinite	Chlorite
12	grayish-green expansive soil	East of Gaobei Village, Huangliangmeng	25	6	9	43	7	10	7

Clay minerals in the Handan samples mainly include smectite, illite and kaolinite. Smectite has a mean content of 33.6% and reaches 57.6% in the grayish-green soil at Caozhuang. Its hydration provides a mineralogical explanation for the measured swelling susceptibility, but mineral abundance alone does not determine field deformation. The grade-specific values in Table 4 show higher smectite contents in the more expansive groups. Comparable work on Ankara clay demonstrates that clay fabric also affects swelling direction and magnitude (Avsar et al. 2009), while Handan swelling tests highlight density and initial-water-content effects (Liu et al. 2019). Thus, composition identifies susceptible materials; the following physical and strength tests evaluate their response to water uptake.

Table 4 Mineral composition of expansive soils (rocks) with different swelling grades in the Handan section

Swelling grade	Mineral composition (mean)					
	Detrital minerals (%)			Clay minerals (%)		
	Quartz	Calcite	Feldspar	Chlorite	Illite	Smectite
Strongly expansive	41	11	1	-	-	45
Moderately expansive	33	23	4	2	-	33
Weakly expansive	40	28	3	-	-	28

4.2 Conventional Properties and Swelling-Shrinkage Characteristics of Expansive Soils

(1) Physical properties and swelling–shrinkage characteristics of expansive soils

Statistical analyses cover 405 sets of physical-property and swelling–shrinkage tests grouped by geological age, lithology and swelling grade (Table 5). For the Qp₁

and N₁ clay groups, the mean <0.005 mm fraction ranges from 38.5% to 52.7%. Within these clay groups, stronger swelling grades generally coincide with higher natural water content, liquid limit and free swell ratio. The loaded and unloaded swelling indices do not all vary monotonically, illustrating the influence of loading and specimen condition; a single index should therefore not be used to infer slope deformation. The listed clay groups have liquid limits above 40%, which can assist local screening but is not a universal classification threshold. These results characterize moisture sensitivity, whereas the compression and shear tests below establish its mechanical consequences. Free swell ratios, swelling strains and gravimetric water contents are distinct quantities and are not interchangeable with the effective saturation calculated in Sect. 5.

Table 5 Physical-property and swelling-shrinkage indices of expansive soils (rocks) along the Handan canal section (mean values)

Lithology	Swelling grade	Natural water content (%)	Clay content (%)	Unit weight (kN/m ³)	Liquid limit (%)	Free swelling ratio (%)	Swelling pressure (kPa)	Unloaded swelling ratio (%)	Swell percent under 50 kPa pressure (%)	Volume shrinkage ratio (%)	Linear shrinkage ratio (%)
Qp ₁ clay	Strongly expansive	29.4	46.5	19.3	60	106	97.7	7.32	1.11	22.5	8.7
	Moderately expansive	26.6	43.7	19.5	51.1	73.7	97.7	12.67	0.99	19.4	7.4
	Weakly expansive	22	38.5	20.1	41.2	51.8	43.4	8.55	0.25	11.7	4.3
N ₁ clay	Strongly expansive	25.2	52.7	19.6	52.5	96.9	65.1	8.57	1.85	18.31	6.47
	Moderately expansive	24.6	49.8	19.9	49.4	75.4	82.6	11.81	0.49	16.24	5.49
	Weakly expansive	21.7	41	20.1	42.8	53	32.8	5.98	0.63	12.67	4.57

N ₁ clay ston e	Strongly expansive	24.4	42.4	/	67	48.1	98.1	56.6	10.95	5.12	18.6
	Moderately expansive	21.7	44.2	/	62.6	44.4	75.1	40.3	9.2	0.78	13.8
	Weakly expansive	20	38	/	60.6	40.7	52	26.2	5.24	0.14	9.6

(2) Unconfined compressive strength of expansive soils

Unconfined compressive-strength tests compare natural, saturated and dried-then-saturated specimens (Table 6), representing contrasting wetting histories rather than exact replicas of field groundwater zones. Every available natural–saturated pair shows strength loss, with softening coefficients of 0.24–0.85. In Qp₁ clay, natural and saturated strengths both increase from strongly to weakly expansive groups. However, the ordering between claystone and clay changes after wetting: moderately expansive N₁ claystone decreases from 0.485 to 0.114 MPa, below the saturated strength of moderately expansive N₁ clay (0.160 MPa). A universal claystone > clay strength ranking is therefore inappropriate. The further reduction in available dried-then-saturated specimens indicates sensitivity to wetting history. This evidence motivates examination of whether rainfall can reach the corresponding subsurface materials through fractures.

Table 6 Statistical results of unconfined compressive-strength tests

Stratigraphic age	Lithology	Swelling grade	Unconfined compressive strength (MPa)			Softening coefficient
			Natural state	Saturated state	Dried-then- saturated state	
Qp ₁	clay	Strongly expansive	0.135	0.092	0.08	0.68
		Moderately expansive	0.235	0.16	0.14	0.68
		Weakly expansive	0.39	0.33	0.154	0.85
N ₁	clay	Strongly expansive	0.26	0.14	/	0.54

		Moderately				
		y	0.28	0.16	/	0.57
		expansive				
		Moderately				
		y	0.485	0.114	/	0.24
	claystone	expansive				
		Weakly	0.39	0.215	0.143	0.55
		expansive				

4.3 Shear Strength of Expansive Soils (Rocks)

(1) Statistical analysis of shear strength of expansive soils (rocks)

Undisturbed borehole and exploratory-well samples were tested in direct shear (Table 7). Both cohesion c and friction angle ϕ span broad ranges, indicating considerable heterogeneity within the lithological and swelling-grade groups. The group means generally increase from Qp₁ clay to N₁ clay and claystone, although cohesion does not follow this ordering in every group. Neither c nor ϕ varies monotonically with swelling grade across all lithologies. Consequently, these statistics describe spatial variability rather than a unique strength–swelling relationship. The repeated direct-shear tests below examine water-content effects for a selected strongly expansive soil and provide a more specific basis for interpreting wetting-related weakening.

Table 7 Shear-strength parameters of expansive soils (rocks) along the Handan section of the Middle Route of the South-to-North Water Diversion Project

Swelling grade		Strongly expansive				Moderately expansive				Weakly expansive			
Stratigraphic age	Lithology	c (kPa)		ϕ (°)		c (kPa)		ϕ (°)		c (kPa)		ϕ (°)	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Qp ₁	clay	30–35	31.8	4.0–22	14.6	15–70	34.6	3.4–22.6	12.2	10–88	41.6	4.6–22.6	13.4
N ₁	clay	5–120	60.3	5.7–36.3	18.3	7.6–120	56.2	4.2–36.8	15.8	8–140	65.4	3.8–37.7	16.6

clayston e	6–90	70.4	14.2– 34.6	22.8	4–145	68.6	4.8–45	21.2	7–162	60.5	1.2– 44.8	20.6
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(2) Repeated direct-shear tests on strongly expansive soil from a typical slope of the Handan canal section

Repeated direct-shear tests were conducted with a four-cell strain-controlled apparatus on remoulded strongly expansive soil from a representative Handan canal slope. Specimens were prepared at initial gravimetric water contents of 15%, 20% and 25%, together with a saturated condition. The stress–displacement curves (Fig. 3) show the combined influence of normal stress and water content on peak and large-displacement shear response. Higher normal stress increases the mobilized resistance under the test conditions, whereas wetting generally reduces it. The latter response is consistent with changes in suction and soil structure, but suction was not independently controlled in these tests. Therefore, the fitted parameters characterize the tested moisture states rather than intrinsic effective-stress constants (Fredlund et al. 1978). The normal-stress effect also does not establish that adding load would improve overall slope stability, because additional loading changes both driving and resisting forces.

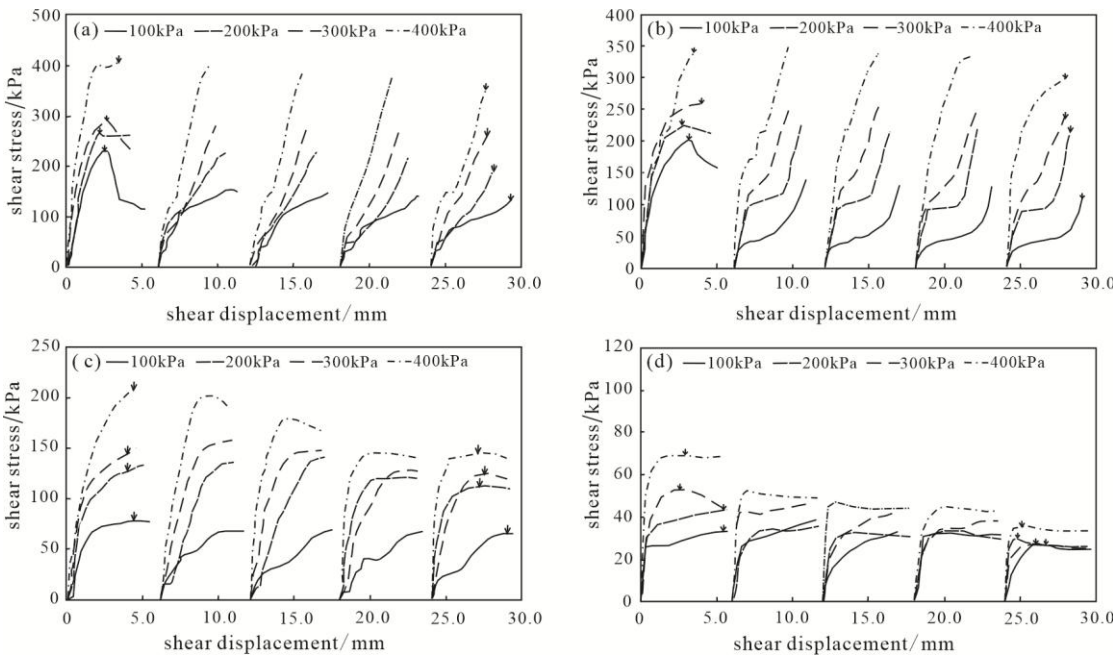


Fig. 3 Shear stress–shear displacement curves of strongly expansive soil under different water contents

(a) water content of 15%; (b) water content of 20%; (c) water content of 25%; (d) saturated state

Table 8 identifies substantial weakening between 20% and 25% gravimetric water content: peak cohesion decreases from 146.9 to 37.1 kPa (74.7%), while the residual friction angle decreases from 30.42° to 13.83°. The saturated specimens show further reductions in the fitted friction angles. Individual parameters are not uniformly monotonic; residual cohesion, for example, increases between 15% and 20%. The 20–25% interval is therefore a moisture-sensitive interval for the tested remoulded soil, not a universal failure threshold. Repeated direct shear also provides an operational large-displacement strength, rather than proof of a field-scale residual-strength state. These tests establish how wetting can reduce resistance. Section 5 then investigates where and when rainfall reaches potentially vulnerable layers; no direct conversion of simulated effective saturation into these strength parameters is assumed.

Table 8 Shear-strength parameters under different water contents

Water content w (%)	Peak shear strength		Residual shear strength	
	c_r (kPa)	ϕ_r (°)	c_r (kPa)	ϕ_r (°)
15	160.8	28.58	55.6	36.03
20	146.9	23.32	66.26	30.42
25	37.1	22.15	50.1	13.83
saturated	21.65	6.48	22.15	1.74

5 Numerical Simulation of Rainfall Infiltration and Slope Response in Expansive-Soil Areas

The laboratory results establish two complementary aspects of material susceptibility: swelling–shrinkage tests indicate sensitivity to moisture change, and strength tests show the mechanical penalty associated with wetting. A further question is whether rainfall can reach susceptible layers beneath the replacement fill. Field studies of expansive-soil slopes demonstrate the importance of fissures in rainfall response (Ng et al. 2003; Zhan et al. 2007), and crack–matrix hydraulic formulations explain why bulk flow cannot be inferred from intact-matrix properties alone (Li et al. 2011). Accordingly, the following seepage scenarios compare water pathways and effective-saturation histories in unfractured and fractured slopes. Laboratory strength data support interpretation of the consequences of wetting; they are not inputs to a mechanical solver here. The analysis addresses hydraulic conditions conducive to

weakening, without calculating displacement, swelling stress, factor of safety or failure time.

5.1 Model Establishment and Design of Simulation Conditions

A representative Handan canal slope was simplified as a model approximately 90 m long and 30 m high, comprising surface fill, shallow expansive soil, silty clay and deep expansive soil (Fig. 4). The slope ratio is 1:2.75. Fractures are placed in the rear (upper) and front (lower) parts of the shallow expansive-soil layer. The mapped stratigraphy defines the geological context, and the tested water sensitivity motivates attention to the potential slip-zone material. The hydraulic parameters in Table 9 describe the sliding mass, slip zone and fracture domains for scenario comparison; a sample-by-sample calibration against the laboratory strength tests is not implied. The comparison uses an unfractured reference and fixed 7 m deep fractures, rather than a continuous range of fracture depths.

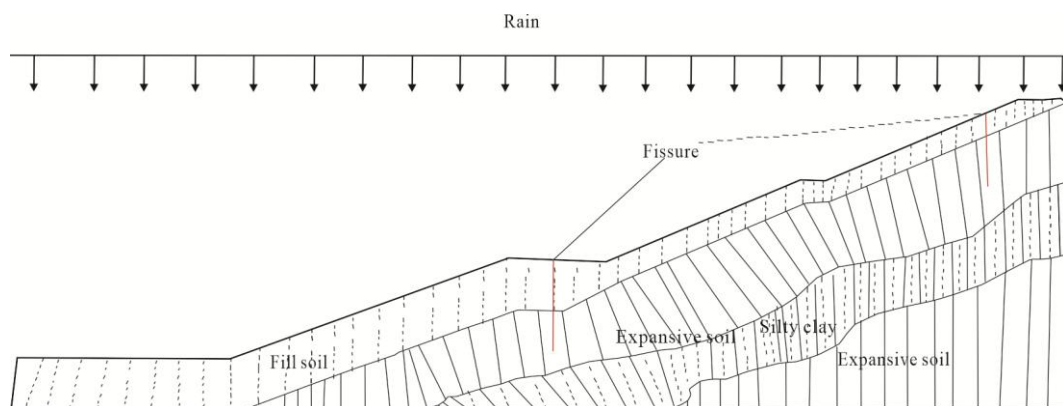


Fig. 4 Simplified geometric model of the expansive-soil slope

The scenarios in Table 10 comprise no fractures, one rear fracture, one front fracture, and both front and rear fractures. Rainfall intensity and elapsed time are compared to identify changes in wetting extent and local saturation timing. Differences between scenarios are interpreted within this fixed geometry and parameter set.

5.2 Analysis of Simulation Results

(1) Response of the seepage field to rainfall infiltration

Variably saturated seepage was calculated using the Richards equation in COMSOL, with the Brooks–Corey hydraulic relationship (Brooks and Corey 1964). Table 9 specifies saturated and residual volumetric water contents of 0.49 and 0.12, and

saturated hydraulic conductivities of 1×10^{-6} , 6.5×10^{-8} and 1×10^{-3} m/s for the sliding mass, slip zone and fractures, respectively. Fractures are represented by fixed high-permeability zones, 7 m deep and up to 0.5 m wide; this width is a modelling idealization, not a measured uniform aperture. Constant rainfall intensities are 3, 1 and 0.3 mm/h for 360 h, giving cumulative inputs of 1080, 360 and 108 mm. The labels heavy, moderate and light used in the figures denote relative model scenarios, not meteorological categories or a reconstruction of the July 2016 event. Eight points record effective saturation (Fig. 5), defined as $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$, where θ is volumetric water content. Thus, $S_e = 1$ denotes local saturation; it is neither a strength value nor a slope-failure criterion.

Table 9 Numerical simulation parameters

Saturated water content θ_s	Residual water content θ_r	Saturated hydraulic conductivity of sliding mass K_{sm} ($m \cdot s^{-1}$)	Saturated hydraulic conductivity of slip zone K_{ss} ($m \cdot s^{-1}$)	Saturated hydraulic conductivity of fractures K_f ($m \cdot s^{-1}$)	Brooks-Corey parameter α_{BC} (m^{-1})	Brooks-Corey parameter n_{BC} (-)	Brooks-Corey parameter r_{BC} (-)	Dynamic viscosity of water μ ($Pa \cdot s$)
0.49	0.12	1×10^{-6}	6.5×10^{-8}	1×10^{-3}	2.8	0.16	1	1×10^{-3}

Table 10 Calculation conditions for the expansive-soil slope

Number	Fracture position	Fracture depth (m)	Number of fractures	Remarks
1	-	-	-	No fractures
2	Rear part	7	1	Front part: no fractures, rear part: 1 fracture each
3	Front part	7	1	Front part: 1 fracture, rear part: no fractures
4	Front part, Rear part	7, 7	1, 1	Front part and rear part: 1 fracture each

1) Effect of the presence or absence of fractures

At 3 mm/h, the unfractured scenario develops a wetting front approximately parallel to the slope surface, reaching about 2 m depth after 150 h (Fig. 6). The scenarios with fractures (Figs. 7–9) provide preferential access to deeper material. Wetting develops near the lower fracture segments and then spreads upward and laterally into adjacent soil. This shows interaction between preferential flow and matrix wetting,

rather than replacement of one flow mechanism by the other. In combination with the laboratory results, the simulated wetting pattern identifies locations where strength degradation is plausible; it does not quantify the resulting strength loss.

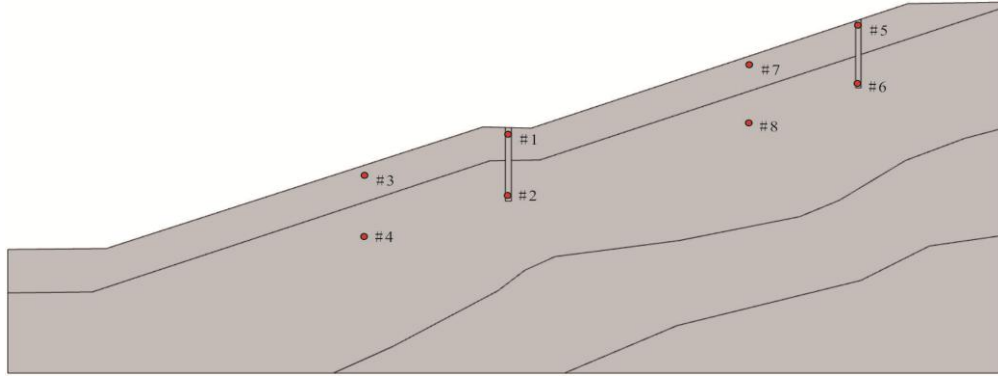


Fig. 5 Layout of effective-saturation monitoring points in the slope

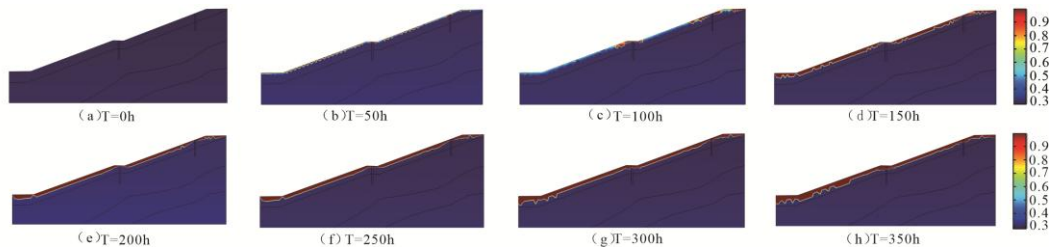


Fig. 6 Effective-saturation distributions of the landslide mass in an unfractured expansive-soil slope under heavy rainfall at different durations

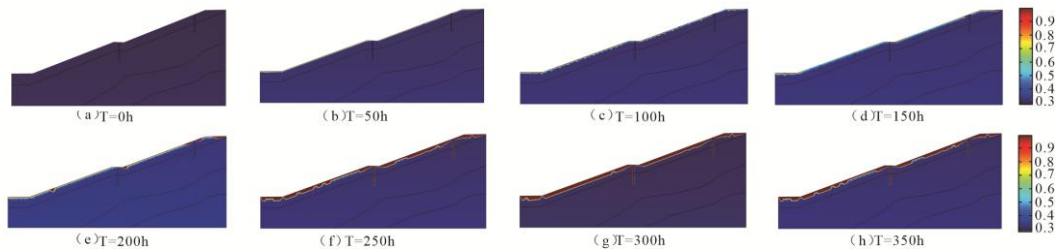


Fig. 7 Effective-saturation distributions of the landslide mass in a fractured expansive-soil slope under light rainfall at different durations

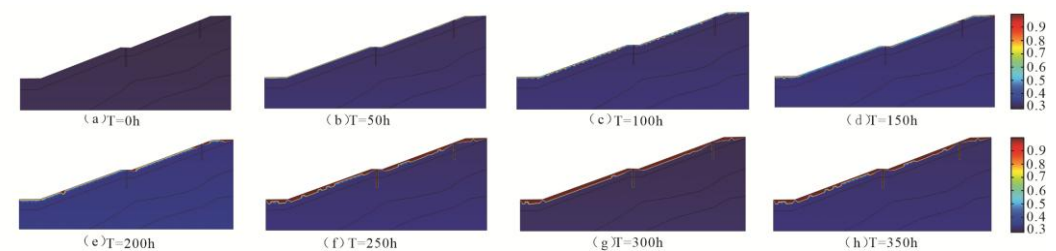


Fig. 8 Effective-saturation distributions of the landslide mass in an expansive-soil slope with front and rear fractures under moderate rainfall at different durations

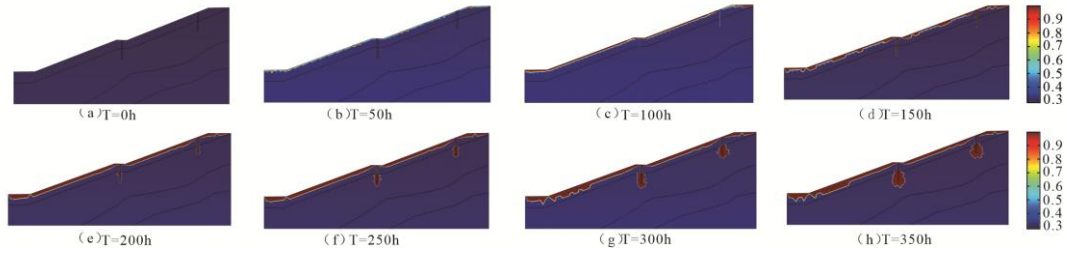


Fig. 9 Effective-saturation distributions of the landslide mass in a fractured expansive-soil slope under heavy rainfall at different durations

As shown in Fig. 10, under heavy rainfall only the shallow monitoring points in the unfractured slope reach saturation, in the order #7, #3, #5, and #1, requiring approximately 100, 130, 240, and 320 h, respectively. The lower monitoring points #8, #6, #4, and #2 remain unsaturated at 350 h, with effective saturation generally remaining at approximately 0.3.

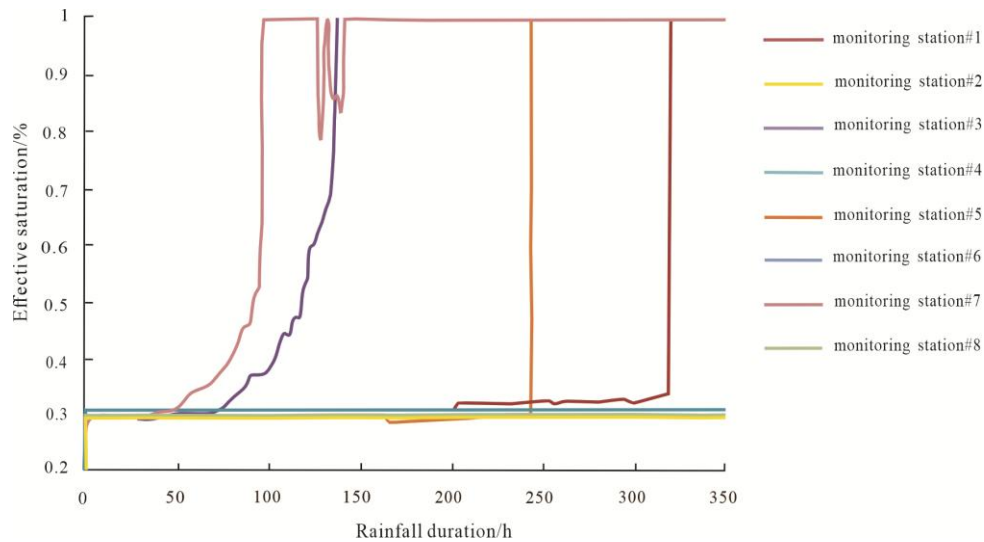


Fig. 10 Temporal variation in effective saturation at monitoring points in the unfractured landslide mass under heavy rainfall

Under the 3 mm/h scenario with front and rear fractures extending to 7 m, Fig. 11 shows saturation at monitoring points close to the fractures and in the shallow cover. The lower fracture points (#6 and #2) respond before their upper counterparts (#5 and #1), followed by shallow points away from the fractures (#7 and #3). Points #4 and #8 remain unsaturated. Thus, the approximately 100 h response at the front slip-zone point characterizes local saturation near a preferential pathway, not saturation of the entire potential slip zone.

Figs. 12 and 13 show that decreasing rainfall intensity delays the time to saturation and reduces the number of monitoring points that can become saturated. Under moderate rainfall, saturation generally occurs at 240–280 h; points #3, #4, and #8 remain unsaturated at 350 h, with effective saturation values of 0.45, 0.3, and 0.3, respectively. Under light rainfall, none of the monitoring points becomes saturated; after 350 h, the effective saturation values at #1–#8 are 0.32, 0.32, 0.4, 0.3, 0.3, 0.3, 0.39, and 0.3, respectively.

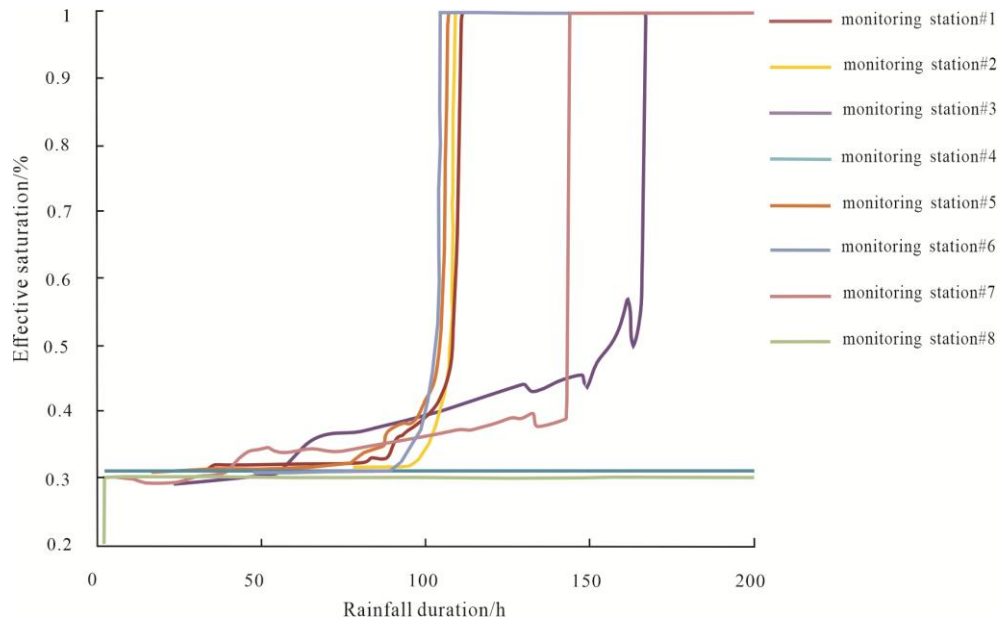


Fig. 11 Temporal variation in effective saturation at monitoring points in the fractured slope under heavy rainfall

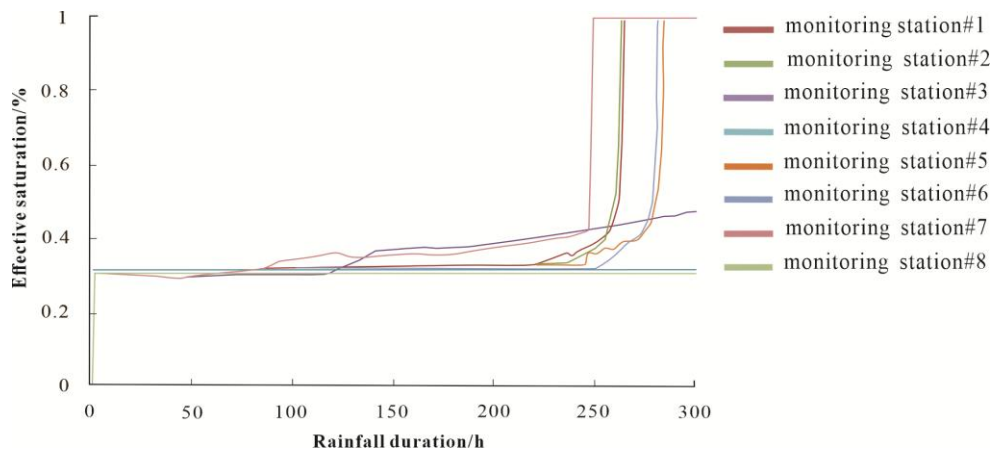


Fig. 12 Temporal variation in effective saturation at monitoring points in the fractured slope under moderate rainfall (front and rear fracture depth = 7 m)

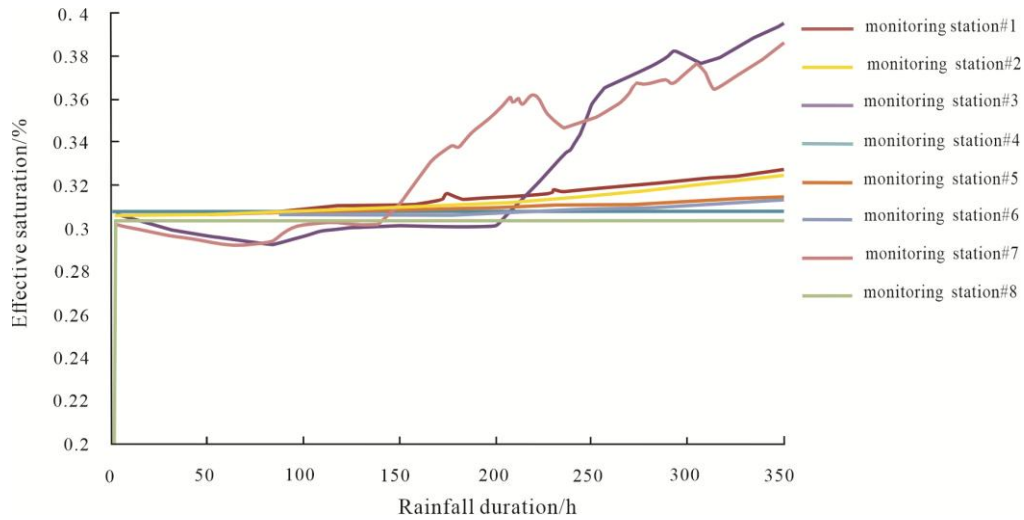


Fig. 13 Temporal variation in effective saturation at monitoring points in the fractured slope under light rainfall

The comparison between the unfractured reference and the fixed 7 m fracture scenarios shows that connected preferential pathways extend rainfall influence below the shallow wetting front. At the front slip-zone monitoring point #2, saturation occurs after approximately 250 h at 1 mm/h and 100 h at 3 mm/h. These results demonstrate sensitivity to fracture connectivity and rainfall forcing for the selected configurations, but two depth states cannot establish a general depth–response law. Moreover, 100 h represents sustained rainfall over several days, not a short storm. The identified saturation times indicate potential exposure to the wetting-induced weakening measured in Sect. 4, rather than the timing of mechanical failure.

2) Effect of fracture location

A single 7 m deep fracture was placed separately at the rear and front of the slope (Figs. 14 and 15). Both configurations transmit water below the shallow layer and change the spatial distribution of saturation. Fracture position determines which parts of the potential slip zone receive preferential inflow, while the local response also depends on hydraulic contrast and flow-path geometry. The point histories in Figs. 16 and 17 should therefore be compared at corresponding locations; they do not establish that front fractures universally produce earlier saturation throughout the slope. A larger contributing catchment is a possible field mechanism, but it cannot be established from effective-saturation curves alone.

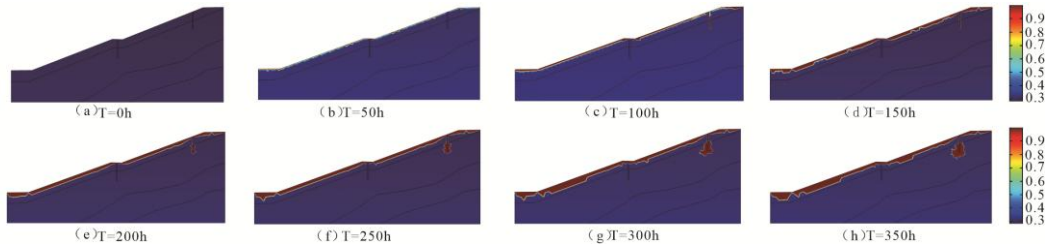


Fig. 14 Effective-saturation distributions for the condition with a fracture at the rear of the slope under heavy rainfall

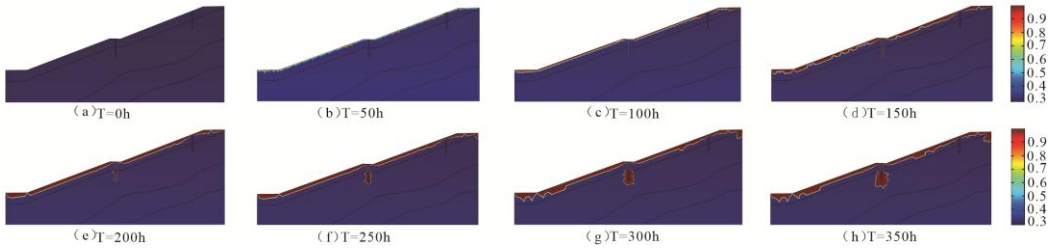


Fig. 15 Effective-saturation distributions for the condition with a fracture at the front of the slope under heavy rainfall

Under the rear-fracture scenario, points #1, #3, #5, #6 and #7 reach saturation (Fig. 16). The rear-fracture points respond from bottom to top around 100 h, followed by #1, #7 and #3 at approximately 110, 130 and 150 h. Under the front-fracture scenario, points #1, #2, #7, #3 and #5 reach saturation (Fig. 17): #2 and #1 at about 110 h, then #7, #3 and #5 at about 120, 170 and 230 h. The different sets and timings show redistribution of wetting, including rapid local access to the front slip zone. They support location-specific monitoring of both rear and front fractures rather than a single ranking of whole-slope saturation speed.

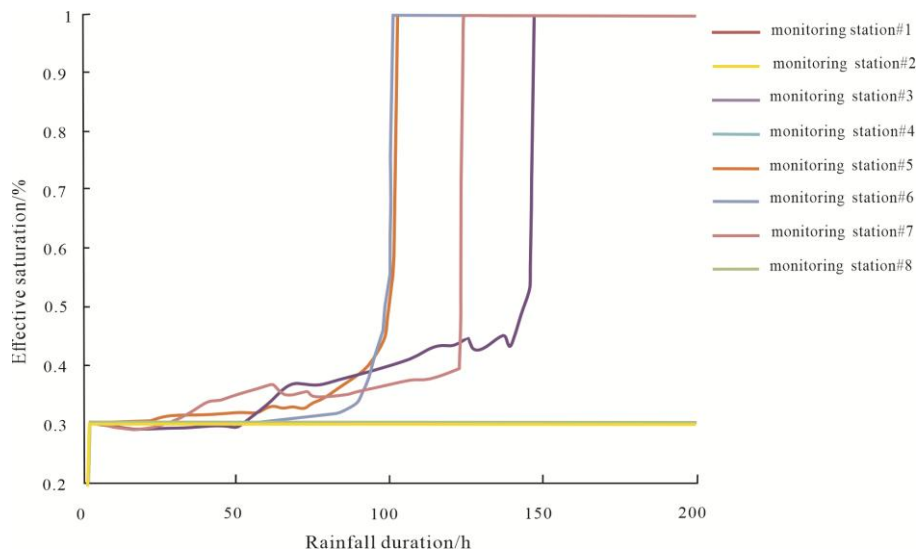
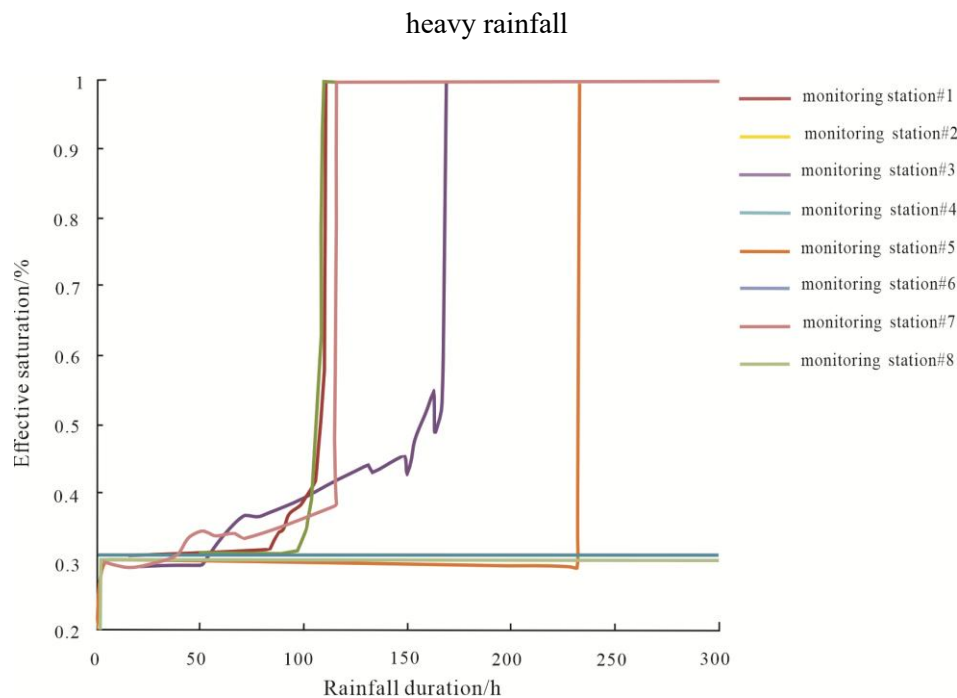


Fig. 16 Effective-saturation monitoring curves for a fracture at the rear of the slope under



485

486 **Fig. 17** Effective-saturation monitoring curves for a fracture at the front of the slope
487 under heavy rainfall

488 **6 Discussion**

489 The field, laboratory and numerical results can be interpreted as a linked sequence
490 of material susceptibility, water access and potential mechanical weakening (Fig. 18).
491 Mapping identifies expansive layers beneath the replacement fill, while mineralogical
492 and swelling tests explain their sensitivity to moisture change. Compression and
493 repeated direct-shear tests demonstrate that wetting can reduce resistance, including a
494 pronounced decrease in peak cohesion between 20% and 25% water content for the
495 tested soil. The seepage scenarios supply the spatial and temporal connection: fractures
496 allow water to bypass the shallow cover and wet deeper material near the potential slip
497 zone. This combination supports two plausible field failure pathways. Where fill
498 remains well bonded to the underlying material, differential swelling and wetting-
499 related weakening may concentrate deformation in the expansive layer or at a
500 geological interface. Where the fill–soil contact is poorly compacted or already weak,
501 localized wetting may favour sliding along that contact. These are interpretations of the
502 combined evidence, not mechanically simulated failure modes. Rainfall is particularly
503 relevant where groundwater remains below the canal invert, but this condition does not

exclude perched water or groundwater contributions in other reaches.

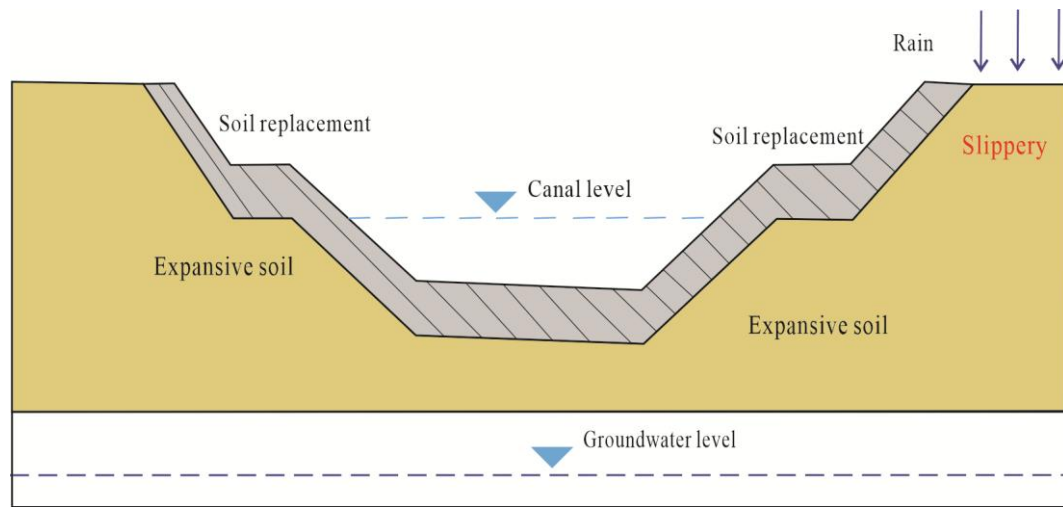


Fig. 18 Conceptual interpretation of water–soil interactions and possible hazard-control measures in expansive-soil areas

The relevance beyond Handan lies in the combination of a moisture-sensitive matrix with structurally controlled water entry. Ankara clay provides a useful comparison for smectite-rich material and fabric-dependent swelling (Avsar et al. 2009), whereas London Clay monitoring and British embankment studies demonstrate the importance of seasonal moisture cycling and weather-related deterioration (Smethurst et al. 2012; Stirling et al. 2021). These soils and climates are not identical to Handan, so the comparison supports a shared process framework rather than transfer of numerical thresholds. The preferential infiltration seen here is also consistent with instrumented expansive-soil slopes and crack–matrix hydraulic formulations (Ng et al. 2003; Zhan et al. 2007; Li et al. 2011). The contribution of the present case is to connect corridor-scale exposure and material testing with explicit fracture scenarios, showing why low matrix permeability alone is insufficient to characterize access of water to deeper susceptible layers.

The laboratory–model linkage remains interpretative. Effective saturation describes a volumetric hydraulic state, whereas the direct-shear tests use gravimetric water content; translating between them requires matched dry density, volume-change information and retention behaviour. Furthermore, shear strength depends on stress path, suction and fabric, not solely on water content (Fredlund et al. 1978; Nowamooz and Masrouri 2008). The remoulded shear specimens do not reproduce the intact field

fracture network. Accordingly, the model identifies potential wetting exposure, while the tests establish a direction of mechanical response; they do not provide a calibrated strength–saturation law. The fixed fracture geometry also excludes swelling-induced closure and drying-induced propagation. Double-structure and desiccation-modelling studies show why these feedbacks matter (Alonso et al. 1999; Tang et al. 2021; Al-Jeznawi et al. 2025).

The hydraulic scenarios lack validation against site pore-pressure or deformation histories and do not include a coupled factor-of-safety analysis. Constant 360 h rainfall, idealized fracture width and incomplete hydraulic calibration limit interpretation of saturation times. Transfer requires initial-state and boundary-condition specification, layer-specific hydraulic properties, numerical convergence checks and field validation. Practically, investigation should target fractures connecting surface water to weak layers, supported by drainage maintenance, contact-zone assessment and monitoring at both slope ends. These scenarios support investigation priorities but do not establish treatment rankings or transferable rainfall-warning thresholds.

7 Conclusions

(1) Expansive soils (rocks) along the Handan section are confined to the ground west of the Beijing–Guangzhou Railway, extending about 50 km along the canal and covering about 220 km². Three genetic types occur: Neogene lacustrine expansive claystone, Lower Pleistocene lacustrine expansive clay, and expansive clay weathered from claystone. The buried type, concealed beneath Qh loam, Qp₃ loess-like soil or a Qp₁ muddy gravel–sand layer, is both structurally more complex and far more extensive than the surface-exposed type, and therefore governs where investigation effort should be concentrated.

(2) The mapped strong, moderate and weak swelling grades occupy about 10.93, 119.07 and 90.00 km², respectively, with strongly expansive occurrences concentrated in ridge-like uplands between Lintan Town and Yinbao Village. The independent 381-group elevation dataset contains 5.8% strongly, 39.1% moderately and 55.1% weakly expansive samples; about 78–82% within each grade occur at 70–90 m. Sample frequencies and mapped area proportions describe different quantita-

ies. The elevation concentration helps identify investigation priorities where these strata intersect deep-cut canal slopes.

(3) Smectite enrichment (mean 33.6%) and swelling–shrinkage behaviour identify moisture-sensitive materials. All available natural–saturated compression pairs show strength reduction, but claystone does not consistently remain stronger than clay after wetting. Repeated direct-shear tests identify pronounced weakening between 20% and 25% gravimetric water content, including a 74.7% decrease in peak cohesion. This interval is specific to the tested remoulded soil and should not be treated as a universal moisture threshold or directly equated with simulated effective saturation.

(4) The unfractured scenario develops a wetting front about 2 m deep after 150 h, whereas 7 m deep fractures enable localized wetting near the potential slip zone. Front slip-zone point #2 reaches saturation at approximately 100 h under 3 mm/h and 250 h under 1 mm/h; no monitored point saturates under 0.3 mm/h during the simulated period. Fracture position changes the distribution and timing of wetting, without establishing a universal front-versus-rear ranking. Combined with the strength tests, these results indicate where rainfall may activate material weakening. The transferable outcome is an assessment sequence linking geological exposure, moisture-sensitive strength and preferential infiltration; absolute saturation times and intervention priorities require local calibration and coupled stability analysis.

Author contributions Jinqiu Li: conceptualization, investigation, data curation, writing – original draft. Zhenxing Wang: conceptualization, supervision, writing – review and editing. Sanshao Ren, Yunpeng Li and Xinwei Hou: field investigation and sampling. Zhanxue Bai and Ming Gao: laboratory testing and data analysis. Jin Sun and Qiang Zhao: numerical modelling. All authors read and approved the final manuscript.

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Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval Not applicable.

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