Dear Editors and Reviewers,

We are very grateful to your help and the comments for the manuscript entitled "Mechanical State of Gravel Soil in Mobilization of Rainfall-Induced Landslide in Wenchuan seismic area, Sichuan province, China". Your valuable comments can effectively help our paper improve. We have revised the manuscript in accordance with your detailed comments. Besides, we have carefully proof-read the manuscript to remove mistakes about language and grammar.
Please find the following responses to the comments of reviewer.
Best wishes.
Liping Liao and behalf of all co-authors

## Reviewer 1

General comments This paper presented a study about the mechanical state of gravel soil in the landslide initiation using artificial flume model tests and triaxial tests. This topic is very interesting and significant for the landslide early identification and prediction, and it is within the scope of ESURF. The experiment and testing are designed reasonably and its results are reliable. but I think the innovation of this paper is slightly weak. The Introduction and Conclusion did not prepare well. In addition, the language of this paper should be improved. I think this paper needs a round of major revision before publication.
**Authors' response:** Thank you for your kind suggestions. The introduction and conclusion has been rewritten. The language of the manuscript has been improved. The revised details can be found in Line 31~77, Line 382-397.

Specific comments
1. I think the introduction was not prepared well. too many previous studies were presented, only important studies related to you study should be presented; the purpose and motivation of this paper should be clearer.
**Authors' response:** Thanks a lot for your comment. Your comment provides the valuable guidance for improving the manuscript. According to your suggestion, the introduction has been rewritten and improved. The revised details can be found in Line31-77.

2. The initial dry density is important for the analysis and conclusions, I suggest the authors add some explanation that why or how these four initial dry densities (1.54g/cm$^3$,1.63g/cm$^3$, 1.72g/cm$^3$, 1.81g/cm$^3$) were selected?
**Authors' response:** Thanks you for your comment. The designed initial dry density is 1.50g/cm$^3$,1.60g/cm$^3$, 1.70g/cm$^3$ and 1.80g/cm$^3$. In order to achieve a predetermined density, the soils of the models are divided into four layers, and each layer is compacted respectively. Therefore, some experiment errors exist; the actual density is 1.54g/cm$^3$,1.63g/cm$^3$, 1.72g/cm$^3$ and 1.81g/cm$^3$. The revised details can be found in Line103~109.

3. In the Section of 3.1, the authors stated that ’throughout the rainfall, the volume moisture content of soil depth of 40cm exhibits a slow-growth trend or remains the stable’; however, as shown in Fig. 6, the volume moisture content of soil depth of 40cm increased sharply, please provide a brief explanation for this phenomenon.

**Authors’ response:** Thanks a lot for your comment. The reason of the phenomenon “the volume moisture content of soil depth of 40cm increased sharply” is its x-label is shorter than *x*-label of other figures. Therefore, all panels have been plotted for the same *x*- and *y*-labels for better comparison. The description about volume moisture content and pore water pressure has been modified accordingly. The revised details can be found in Section 3.2.

4. The authors design the experiment to explore the relationship between the initial dry density and landslide initiation. With the results, it was proved that they have a very close relationship. But, it is still not clear that what the relationship is. For example, why the initiating time of the landslide with the initial dry density of 1.72g/cm3 (18 minutes) is shorter than the landslide with the initial dry density of 1.54-1.63g/cm3 (30 40 minutes). A deep analysis is needed.

**Authors’ response:** Thank you for your kind suggestion. A deep analysis on the relationship between initial dry density and landslide initiation has been added. The revised details can be found in Section 3.1. The revised details can be found in Line 165-187.

5. In the Section of Critical state of gravel soil, the gravel soil with an initial dry density of 1.94g/cm3 and 2.00g/cm3 were used, why not the soil sample used before (1.54-1.81g/cm3)?

**Authors’ response:** Thank you for your kind suggestion. The one reason is that according to the research (Gabet and Mudd 2006; Iverson et al., 2000), the soil with the same granular composition can obtain the approximate critical void ratio in the uniform stress condition. The other reason is that the authors tried to make the soil sample with 1.54-1.72g/cm$^3$, but the soil sample could not maintain stable when it suffers from the gravity of axial loading system. Based on the above reasons, the density of the soil sample for trixial test is 1.94g/cm$^3$ and 2.00g/cm$^3$.

6. In my opinion, the conclusion section was not written well. the 5th conclusion is not clear; I suggest the conclusions about the Critical state of gravel soil can be synthesized. Technical corrections Line 36-41: please cite only the important references, it is unnecessary to list all the related literature; Line 91: I suggest the authors provide a location map with Niujuan Valley and Duwen highway. Line 93: please check the unit of ’32.7Line 116: what does ’CAS’ mean, please provide its definition. Line 120: what does ’DL2e’ mean; Line 166-167: please correct the sentence; Line 240-241: please check the langue; Tab 2: please check the value of initial dry density, 1.62 or 1.63? it is not clear the meaning of h(cm), soil depth? Tab 3: it is not clear the meaning ofâ ̆U¸sP0.0075, â ̆U¸sP5, â ̆U¸sP2 and h. Tab 4: please

provide the definition of $\sigma 3$; Fig.7-9: please add captions for each subfigure.

(1) In my opinion, the conclusion section was not written well. the 5th conclusion is not clear; I suggest the conclusions about the Critical state of gravel soil can be synthesized.

**Authors' response:** Thanks a lot for your kind suggestion. The conclusion has been rewritten. The revised details can be found in Line 382-397.

(2) Line 36-41: please cite only the important references, it is unnecessary to list all the related literature.

**Authors' response:** Thanks a lot for your kind suggestion. The unimportant references have been removed. The revised details can be found in Line 37.

(3) Line 91: I suggest the authors provide a location map with Niujuan Valley and Duwen highway.

**Authors' response:** Thanks a lot for your kind suggestion. The location map of the study area was provided. The revised details can be found in Line 89.

(4) Line 93: please check the unit of '32.7

**Authors' response:** Thanks a lot for your kind suggestion. The unit of '32.7 has been checked. 32.7% is the gradient of valley bed, which is equal to the ratio of the height and the length of the valley. So this value is dimensionless.

(5) Line 116: what does 'CAS' mean, please provide its definition.

**Authors' response:** Thank you for your comment. CAS is the abbreviation of Chinese Academy Science. Its definition has been added to Line 110, Line 123.

(6) Line 120: what does 'DL2e' mean;

**Authors' response:** Thank you for your comment. DL2e is the model of the data acquisition system. The revised details can be found in Line 117-119.

(7) Line 166-167: please correct the sentence;

**Authors' response:** Thank you for your comment. The sentence has been corrected. The revised details can be found in Line 252~267.

(8) Line 240-241: please check the langue;

**Authors' response:** Thank you for your comment. The language of Line 240-241 has been modified. The revised details can be found in Line 305~308.

(9) Tab 2: please check the value of initial dry density, 1.62 or 1.63? it is not clear the meaning of h(cm), soil depth?

**Authors' response:** Thank you for your comment. 1.63 is the correct value. The value of initial dry density in Tab 2 has been modified. *h* is the soil depth and its meaning has been added to Tab.2 and Fig.2(a)

(10) Tab 3: it is not clear the meaning ofâ ″U¸sP0.0075, â ″U¸sP5, â ″U¸sP2 and h.

**Authors' response:** Thanks a lot for your kind suggestion. The cumulative content of coarse (particle diameter > 5mm) is represented by $P_5$, the cumulative content of gravel (particle diameter < 2mm) is represented by $P_2$, and the cumulative content of silt and clay (particle diameter < 0.075mm) is represented by $P_{0.075}$. The meanings of $P_5$, $P_2$ and $P_{0.075}$ have been given in section 2.2.3. The revised details can be found in Line 139~141.

(11) Tab 4: please provide the definition of σ3;

**Authors' response:** Thanks a lot for your kind suggestion. The definition of $\sigma_3$ has been added to Tab.4.

(12) Fig.7-9: please add captions for each subfigure;

**Authors' response:** Thanks a lot for your kind suggestion. Due to the adjustment of the structure of Section 3, the figure numbers have been changed. For example, Fig.7-9 is changed to Fig.4~7. The captions of each sub-figures of Fig.4~Fig.7 have been added to the manuscript. The revised details can be found in Line 207~223.

## References


Gabet, E. J.and Mudd, S. M.: The mobilization of debris flows from shallow landslides. Geomorphology, 74, 207-218, doi: 10.1016/j.geomorph.2005.08.013, 2006.

Iverson, R. M., Reid, M. E., Iverson, N. R., LaHusen, R. G.and Logan, M.: Acute sensitivity of landslide rates to initial soil porosity. Science, 290, 513-516, doi: 10.1126/science.290.5491.513, 2000.

## Reviewer 2

With flume and triaxial tests, this paper investigates the mechanical state of gravel soil in Niujuan valley, Sichuan, China. The authors mentioned that they observed the variation is soil moisture content and pore water pressure, and the macro-micro property. They said to have presented a mathematical expression of critical state of soil. And finally discuss the mechanical state of gravel soil. The topic is very interesting.

However, no new mathematical formulation and model appeared in the text, except for some regression fits. There are several inconsistent statements. Lots of data are presented, great job! But, with much less insights and implications. Both the quality of science and presentation is poor. About 1/2 of the MS is very quantitative and geotechnical, while another 1/2 is very descriptive. How do you relate these data to field events? What are the implications for the surface flow process and run-out modelling? These are not very strongly connected. Large part of the manuscript would perhaps better fit to some geotechnical and civil engineering journals than E-Surf. E.g.L137-153; L191-312. Probably these data would be interesting more to geotechnicians, and perhaps less to the audience of earth surface process. Otherwise, strongly justify how this is not the case. The journal and the Editors can decide on it.
**Authors' response:** Thank you for your comment. Your comment provides the valuable guidance for improving the manuscript. According to your suggestions, the inconsistent statements have been removed; several sections of the manuscript have been rewritten; the mechanical insights have been added to the manuscript.

The font size is too small. It was very difficult for me to read the print even with the power glasses. Time to time there are > 25 citations at a place! What is the use/purpose of this? This is fully distracting! Why don't you properly utilize the space for useful science/research? I thought the Journal/Editor should also have some initial controls on these and other aspects, at least the basic quality and content of the manuscript, before it is sent for reviews.
**Authors' response:** Thank you for your comment. The citations have been reduced to 3 citations.

English, in general is good, but time to time difficult to follow, often strange, and needs to be substantially improved.
**Authors' response:** Thank you for your comment. The languages of the manuscript have been improved.

Detailed and critical comments:
L23: "state parameter ...": The audience would not know this here without explaining what they are.
**Authors' response:** Thank you for your comment. The meaning of state parameter has been added to the introduction. The revised details can be found in Line 25.

L26: "forecast": It is not clear, also in the main text, how you could forcast, what does it mean? Can you predict cracks formation and propagation, time, location and scale for forcasting and warning? No method is presented for this. If possible, please explain clearly how you could do that with the data and the models you are discussing.

**Authors' response:** Thank you for your comment. The introduction of the manuscript has been revised.

L31,32: Improve English (ENG.). E.g., were locating –> were located, etc.

**Authors' response:** Thank a lot for your kind suggestion. The language has been improved. The revised details can be found in Line 32-34, Line79.

L36-41: There are > 25 citations here! What is the use/purpose of this? I would suggest to reduce it to about 3.

**Authors' response:** Thank a lot for your kind suggestion. The citations have been reduced to 3 citations. The revised details can be found in Line 37.

L42: "Fully understanding": Never possible. Improve writing.

**Authors' response:** Thank a lot for your kind suggestion. This sentence has been rewritten. The revised details can be found in Line 40-41.

L42-46: Looks like introductory undergraduate text.

**Authors' response:** Thank you for your comment. The introduction of the manuscript has been rewritten. The revised details can be found in Line 38-63.

L50: "Some of the observed phenomena of landslides": Not clear which?

**Authors' response:** Thank you for your comment. The observed phenomena of landslides included the Salmon Creek landslide in Marin County (Fleming et al., 1989), Slumgullion landslide in Colorado (Schulz et al., 2009), and Guangming New Distinct landslide in Shenzhen (Liang et al., 2017). The revised details can be found in Line 50-52.

L53-55: Again, so may citations. Do you need all these at once? Limit to about 3.

**Authors' response:** Thank you for your kind suggestion. The citations have been reduced to 3 citations. The revised details can be found in Line 49-50.

L57: Readers would under at this point what F is?

**Authors' response:** Thank you for your kind suggestion. The F line was drawn by Casagrande (Casagrande A 1936) to distinguish the dilative zone and the contractive zone. This line's horizontal and vertical coordinate is effective normal stress and void ratio. The meaning of F line has been added to Line 47-48.

L59: "the intermittent debris flow": what is it?

**Authors' response:** Thank you for your comment. The statement of this sentence has been improved. The revised details can be found in Line 55.

L60-69: Strange writing. Unnecessary details, some irrelevant, not connected.

**Authors' response:** Thank you for your comment. Unnecessary details have been removed. In addition, the introduction of the manuscript has been rewritten. The revised details can be found in Line 38-64.

L74: "landslide velocity": Which velocity? Initiation, or dynamical until runout? You did not present data and analysis for velocity. Also, the dynamic velocity would, at most, negligibly depend on the initial state you are referring to. Otherwise, present data and analysis to support your arguments.

**Authors' response:** Thank you for your comment. The statement was provided by William (Schulz et al., 2009). He pointed out the dilative strengthening might control the velocity of a moving landslide though the hourly continuous measurement of displacement of landslide. Therefore, "landslide velocity" is the velocity of the dynamic movement of landslide. The revised details can be found in Line 59-60.

L75-80: Again, > 25 citations at one place. This is fully distracting! Why don't you properly utilize the space for useful science/research?

**Authors' response:** Thank you for your kind suggestion. The citations have been reduced. The revised details can be found in Line 63-67.

L81-80: "the critical state of gravel soil in a seismic area is not exactly identified in the field research": Why does it matter if it is sesimic or not?

**Authors' response:** Thank a lot for your comment. Gravel soils are generated by seismic shaking in Wenchuan earthquake area (Tang and Liang 2008; Xie et al., 2009). The feature of this soil is wide grading, under-consolidation and low density. In addition, according to the existing literatures, the research on the critical state of gravel soil is lacking at present. Therefore, this study is necessary and has the local characteristic.

L96, 102: "large scale", "most of rainfall induced landslides is the shallow landslides": inconsistent presentations. What is large scale?

**Authors' response:** Thank you for your kind suggestion. According to the field investigations, debris flow is large scale. So the statement has been improved. The revised details can be found in Line 86.

L103-104: "silt and clay (particle diameter < 0.075mm) is about 2\%, which plays the important role in the mobilization of landslide and debris flow": How? Without proof and discussion, statements are useless.

**Authors' response:** Thank you for your kind suggestion. Chen (Chen et al., 2010) provided the valuable evidence for quantifying clay content impact on gravel soil failure and the initiation of debris flow. He concluded that silt and clay content played the important role in the mobilization of landslide and debris flow. Therefore, authors only cited his conclusion in the manuscript. The revised details can be found in Line 100-102.

L119: "produced in England": Do you need to say this? Why not to use reference properly?

**Authors' response:** Thank you for your kind suggestion. The unnecessary information "produced in England" has been removed. The revised details can be found in Line 116-118.

L127-129: Fig. 1a: Initial shape and wedge angle needs to be discussed, also why chosen this way?

**Authors' response:** Thank you for your kind suggestion. The reasons for choosing initial conditions of test have been added to Section 2.2.1. The revised details can be found in Line 95, Line 102-109, Line 113-115.

L143: "The mean effective stress p' is equal to one third of the sum of $\sigma x$ , $\sigma y$ and $\sigma z$":Do you really need to say this? There are lots of unnecessary things, making the MS much less professional.

**Authors' response:** Thank you for your kind suggestion. The statement of these problems has been revised in this manuscript. In addition, although this sentence represents the traditional theory of soil mechanics, it is also useful for the manuscript because p' is an important parameter of the soil state, which represents the stress condition of a certain point in the artificial flume model. If the formula of p' is not stated in the manuscript, the reader cannot understand Table 2. The revised details can be found in Line 141.

L145: "is the soil bulk density": No!

**Authors' response:** Thank you for your comment. $\gamma$ is the unit weight of soil. The definition of $\gamma$ has been modified. The revised details can be found in Line 143.

L156-160: Eng.

**Authors' response:** Thank you for your kind suggestion. Section 3.2 has been rewritten. The revised details can be found in Line 226-268.

L168-175: The yellow lines in Fig. panels cannot be seen. Better, plot in different line styles. Explain why the yellow lines are mostly in between the other lines on the right panels? All panels must be plot for the same x- and y-labels for better comparison. The mechanical and geotechnical reasons for the spacial behaviors seen in these panels are not well explained. Furthermore, how these behaviors influence dilation, landslide initiation, velocity and run-out?

**Authors' response:** Thank you for your kind suggestions. (1) The line styles have been modified and all panels have been plotted for the same x- and y-labels. The revised details can be found in Line 268-275. (2) The reason for the yellow line's location had been added to section 3.2. The mechanical and geotechnical reasons for the spacial behaviors seen in these figures were explained. The revised details can be found in Line 226-267. (3) The influence of volume moisture content and pore water pressure on dilation, landslide initiation has been added to section 4. The revised details can be found in Line 364-380.

L178: "the landslide can be triggered by rainfall": Show the hydro-mechanical relationship with the above figure. Otherwise, what is the use of the above data?
**Authors' response:** Thank you for your kind suggestion. A camera was used to record the macroscopic process of the entire experiment. Thus landslide triggered by rainfall was the phenomenon of the model tests. In addition, the hydro-mechanical relationship with the above figures had been added to Section 3.2.

L184-185: Eng.
**Authors' response:** Thank you for your kind suggestion. The language has been improved. The revised details can be found in Line 159-164.

L185-186: "For example, when the initial dry density is 1.54~1.63g/cm3, the initiating time of landslide is 30~40 minutes": You must relate this with Fig. 6, right panels. No insight about the mechanics and process are mentioned, linked, and discussed. Otherwise, what is the use of Fig. 6?
**Authors' response:** Thank you for your kind suggestion. The differences between Fig.8~Fig.11 has been added to Section 3.2 (Line 226-267). The mechanics and process linking with these figures have been added to Section 3.1 and 3.2.

L191: "expansion of cracks": Show it and the dynamics.
**Authors' response:** Thank you for your kind suggestion. Fig.6 (c) has been added to show the propagation of cracks. The revised details can be found in Line 218.

L192: "and rotation": how, where do you see it?
**Authors' response:** Thank you for your kind suggestion. This phenomenon is not my observation, but is observed by other researchers (Gao et al., 2011; Igwe 2014). The relative references have been citied. The revised details can be found in Line 160.

L193-194: "All the above process can lead to the decrease of the void ratio and the increase of the pore water pressure": Not clear how?
**Authors' response:** Thank you for your kind suggestion. This statement has been improved. The revised details can be found in Line 158-164.

L195-196: "When the initial dry density is 1.81g/cm 3, the slope keeps stable and landslide cannot be triggered by the rainfall even though the fine particles disappear, and the coarse particles are exposed at the slope surface.": This is important. Explain with strength relation.
**Authors' response:** Thank you for your kind suggestion. The reasons for this

phenomenon have been added. The revised details can be found in Line 191-197.

L196-205: The figure captions don't explain the process in panels, difficult to follow.
**Authors' response:** Thank you for your kind suggestion. The captions for each sub-figure of Fig.4-Fig.7 have been added. The revised details can be found in Line 201-223.

L252-254: Difficult to follow.
**Authors' response:** Thank you for your kind suggestion. The definition of critical state has been improved. The revised details can be found in Line 319-323.

L262: Is this equation used, and connected to the data?
**Authors' response:** Thank you for your kind suggestion. The formula (2) was used to calculate the critical void ratio. The revised details can be found in Line 323-326.

L266-267: "which can indicate that gravel soil also has the similar principle that the soil with the same grade will shear to reach the same critical void ratio.": But, q and p' differ substantially, explain why.
**Authors' response:** Thank you for your comment. This principle is from the "critical state soil mechanics" (Casagrande A 1936; Roscoe et al., 1963; Schofield and Wroth 1968), which has been validated by many researchers (Fleming et al., 1989; Gabet and Mudd 2006; Iverson et al., 2000)). The revised details can be found in Line 331-332.

L269: "The fitting curve": Mainly the fit curves are presented, almost no mechanical and process explanations.
**Authors' response:** Thank you for your kind suggestion. The mechanical meaning of the fitting curve has been added. The revised details can be found in Line 341-344.

L282-287: Not clear why. Also improve Eng.
**Authors' response:** Thank you for your kind suggestion. Section 4 has been rewritten. The revised details can be found in Line 354-361.

L291-292: Fig. 12: What is the difference between filled dots, and open triangles? Also, there is no correlation between them. I don't see the validity of extrapolation. Otherwise, explain these aspects.
**Authors' response:** Thank you for your kind suggestion. Six filled dots represent the critical state of soil; their values, including $e_c$ and ln$p'$, can be derived from triaxial tests (Tab.4). In addition, the critical state line is obtained by fitting these values (Line 335-339). The hollow dots represent the current states of the soils; the state parameters ($e$, $p'$) can be derived from the artificial flume model tests (Tab.2).

These dots have a close correlation. The critical state line can divide the graphical space into two states. The space above this curve is the contractive zone, and the space below this curve is the dilative zone. If the state parameter ($e$, $p'$) is determined, the soil state can be judged by this line (Gabet and Mudd 2006; Iverson et al., 2000). Therefore, the mechanical state of soil in the artificial flume model can be determined according to Fig.14.

Although there are three confining pressures in triaxial tests, the fitting curve of $e_c$ and ln$p'$ still has a significant statistical meaning due to its high correlation coefficient. In future, multiple confining pressures will be considered in tests to validate the extrapolation of this curve.

L296-298: Does not follow, not clear.

**Authors' response:** Thank you for your kind suggestion. Section 4 has been rewritten. The revised details can be found in Line 364-380.

## References


Casagrande A: Characteristics of cohesionless soils affecting the stability of slopes and earth fills. Journal of the Boston Society of Civil Engineers, 23, 13-32, 1936.

Chen, N. S., Zhou, W., Yang, C. L., Hu, G. S., Gao, Y. C.and Han, D.: The processes and mechanism of failure and debris flow initiation for gravel soil with different clay content. Geomorphology, 121, 222-230, doi: 10.1016/j.geomorph.2010.04.017, 2010.

Fleming, R. W., Ellen, S. D.and Algus, M. A.: Transformation of dilative and contractive landslide debris into debris flows-An example from marin County, California. Engineering Geology, 27, 201-223, 1989.

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Roscoe, K. H., Schofield, A. N.and Thuraijajah, A.: Yielding of clays in states wetter than critical. Geotechnique, 13, 211-240, 1963.

Schofield, A. N.and Wroth, C. P. Critical state soil mechanics. University of Cambridge, 1968.

Schulz, W. H., McKenna, J. P., Kibler, J. D.and Biavati, G.: Relations between hydrology and velocity of a continuously moving landslide - evidence of pore-pressure feedback regulating landslide motion? Landslides, 6, 181-190, doi: 10.1007/s10346-009-0157-4, 2009.

Tang, C.and Liang, J. T.: Characteristics of debris flows in Beichuan epicenter of the Wenchuan earthquake triggered by rainstorm on september 24, 2008. Journal of Engineering Geology, 16, 751-758 (in Chinese), doi: 10.1016/j.geomorph.2005.08.013, 2008.

Xie, H., Zhong, D. L., Jiao, Z.and Zhang, J. S.: Debris flow in Wenchuan quake-hit area in 2008. Mountain Research, 27, 501-509, 2009 (in Chinese).

# Mechanical State of Gravel Soil in Mobilization of Rainfall-Induced Landslide in Wenchuan seismic area, Sichuan province, China

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**Abstract** Gravel soils generated by Wenchuan earthquake have undergone natural consolidation for the past decade. However, geological hazards, such as slope failures with ensuing landslides, have continued to pose the great threats to the region. In this paper, artificial model tests were used to observe the changes of soil moisture content and pore water pressure, as well as macroscopic and microscopic phenomena of gravel soil. In addition, the mathematical formula of the critical state was derived from the triaxial test data. Finally, the mechanical states of gravel soil were determined. The results had five aspects. (1) The time and mode of the occurrence of landslide were closely related to the initial dry density. The process of initiation was accompanied by changes in density and void ratio. (2) The migration of fine particle and the rearrangement of coarse-fine particle contributed to the reorganization of the microscopic structure, which might be the main reason for the variation of dry density and void ratio. (3) If the confining pressure was same, the void ratios of soils with constant particle composition would approach to approximate critical values. (4) Mechanical state of gravel soil can be determined by the relative position between state parameter ($e$, $p'$) and $e_c$-$p'$ planar critical state line, where $e$ was the void ratio, $e_c$ was the critical void ratio and $p'$ was the mean effective stress. (5) In the process of landslide initiation, dilatation and contraction were two types of gravel soil state, but dilatation was dominant. This paper provided an insight to interpret landslide initiation from the perspective of critical state soil mechanics.

**Keywords** Mechanical state • gravel soil• landslide• critical state• Wenchuan seismic area



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## 1 Introduction

In 2008, the gravel soil generated by Wenchuan earthquake produced a large amount of loose deposits (Tang and Liang 2008; Xie et al., 2009). These deposits had features such as wide grading, weak consolidation and low density. They were located on both sides of roads and gullies, and led to the formation of soil slopes (Cui et al., 2010; Qu et al., 2012; Zhu et al., 2011). Although gravel soils have subjected to natural consolidation process for nearly a decade, geological hazards, such as slope failures with ensuing landslides, are readily to motivate in rainy season. At present, geo-hazards still pose the great threats to the region (Chen et al., 2017; Cui et al., 2013; Yin et al., 2016).

The variation of mechanical state, such as the transformation from a relatively stable state to a critical state, has been commonly used to analyze the initiation of landslides (Iverson et al., 2010; Iverson et al., 2000; Liang et al., 2017; Sassa 1984; Schulz et al., 2009). Therefore, a deep understanding of the soil state is the scientific basis for the study of landslide occurrence (Chen et al., 2017). Generally, the critical void ratio is an important parameter to determine the state of soil quantitatively (Been and Jefferies 1985; Schofield and Wroth 1968). The theoretical research had its origins in Reynold's work in 1885. He defined the characteristic of the volumetric deformation of granular materials due to shear strain as dilatation (Reynolds 1885). Casagrande (1936) pointed out that loose soil contracted, and dense soil dilated to the same critical void ratio in the drained shearing test. He drew the F line to distinguish the dilative zone and the contractive zone. The F line's horizontal and vertical coordinate is effective normal stress and void ratio. Since the 1980s, critical state soil mechanics received extensive attentions (Fleming et al., 1989; Gabet and Mudd 2006; Iverson et al., 2000). Some of the observed landslides, such as the Salmon Creek landslide in Marin County (Fleming et al., 1989), Slumgullion landslide in Colorado (Schulz et al., 2009), and Guangming New Distinct landslide in Shenzhen (Liang et al., 2017), might be approximately explained by this theroy. Based on the F line drawn by Casagrande (1936), Fleming (1989) found that the increase of pore water pressure contributed to the dilation, and causes the debris flow characterized by the intermittent movement. Iverson (1997; 2000) pointed out porosity played an important role in the occurrence of landslide; in the soil shearing process, the density of loose sand increased, and the density of dense sand decreased to the same critical density. The formula of the void ratio was derived, which was the function of the mean effective stress (Gabet and Mudd 2006). William et al (2009) found out the dilative strengthening might control the velocity of a moving landslide through the hourly continuous measurement of displacement of landslide. Liang et al (2017) found that the initial solid volume fraction affect the soil state of the granular-fluid mixture. Other scholars also found that in the shearing process, dilation or contraction was exiting in residual soil, loess and coarse-grained soil (Dai et al., 2000; Dai et al., 1999a; Dai et al., 1999b; Liu et al., 2012; Zhang et al., 2010).

The above researchers provided the meaningful insights to explain the occurrence of landslides and drawn the instructive conclusion, such as the initial density or porosity can affect the mechanical state of soil (Iverson et al., 2000) and the formation of landslide (McKenna et al., 2011). However, most of them focused on qualitative results and lacked mutual verification between indoor test and model test. In addition, for the gravel soil generated by seismic, the study on its mechanical state is lacking. Some scientific issues need to be solved. For example, what are the differences and similarities of landslide occurrence? Why does the void ratio or the density change? Is the mechanical state, a contraction or dilation? The purpose of this paper is to solve the above issues through artificial flume model tests and triaxial tests. Firstly, the macroscopic phenomena were



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observed and summarized. Secondly, the variations of soil moisture content and pore water pressure were analyzed. Thirdly, the microscopic property of soil was obtained. Fourthly, the mathematical expression of critical state of soil was proposed. Finally, the mechanical state of gravel soil was determined by the relative position between state parameter ($e$, $p'$) and $e_c$-$p'$ planar critical state line.

# 2 Field site and method

## 2.1 Field site

Niujuan Valley is located in Yingxiu town of Wenchuan County, Sichuan Province, which is the epicenter of 12 May 2008 Wenchuan earthquake in China (Fig.1). The main valley of the basin has an area of 10.46km$^2$, and a length of 5.8km. The highest elevation is 2693m, and the largest relative elevation is 1833m. The gradient ratio of the valley bed is 32.7%~52.5% (Tang and Liang 2008; Xie et al., 2009). Six small ditches are distributed in the basin. Most of the valley is covered with the abundant gravel soil. Extreme complicate terrain and adequate rainfall triggers the frequent landslides and the large-scale debris flows. Thus, this valley is the most typical basin in the seismic area. Its excellent landslide formative environment can provide comprehensive reference models and abundant soil samples for artificial flume model tests.

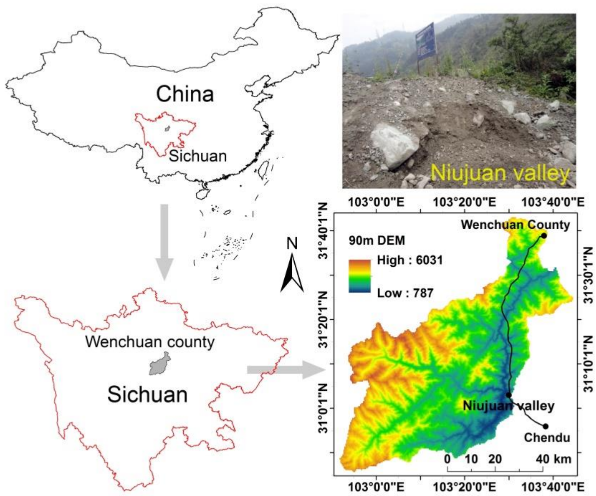


**Fig. 1** Study area

## 2.2 Soil tests and quantitative analysis

### 2.2.1 Artificial flume model test

Based on the field surveys along Duwen highway, Niujuan valley and the literature review (Chen et al., 2010; Fang et al., 2012; Tang et al., 2011; YU et al., 2010), most of the rainfall induced landslides is shallow. The range of the slope angle is 25 °~40 ° and its average value is 27 °. The rainfall intensity triggering the landslide is 10mm/h~70mm/h. As shown in Fig.2(a). The length, width and height of the flume model are 300cm, 100cm and 100cm.

The gravel soil samples are from Niujuan valley. The specific gravity is 2.69. The range of dry density is 1.48~2.36g/cm$^3$; in addition, the minimum and the maximum void ratio is 0.14 and 0.82. Fig.2(b) shows that the cumulative content of gravel (diameter<2mm) and silt and clay (diameter<0.075mm) is 30.74% and 2.78%. The content of silt and clay plays the important role in



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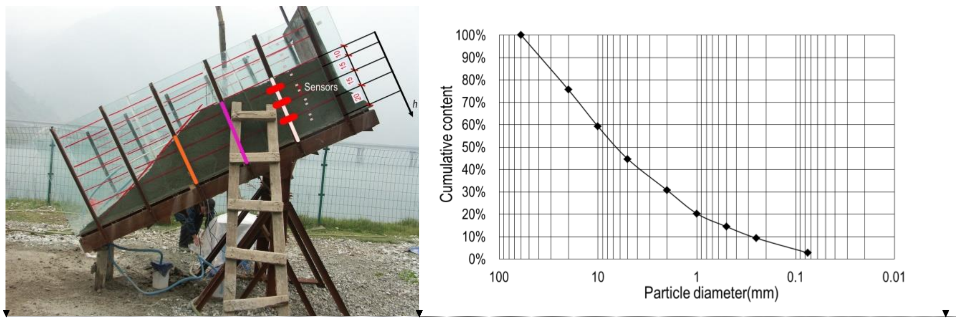
the mobilization of landslide and debris flow (Chen et al., 2010). Four initial dry densities are designed as 1.50g/cm$^3$,1.60g/cm$^3$, 1.70g/cm$^3$ and 1.80g/cm$^3$. According to the previous investigations, the water content mainly changes within a depth less than 50cm, and its average value varies from 6%~8%, while water content below 50cm basically keeps stable. Therefore, the total thickness of the soil model is 60cm. In order to achieve a predetermined initial dry density, the soils of the models are divided into four layers, and each layer is compacted respectively. The thickness of each layer is 20cm, 15cm, 15cm and 10cm (Fig.2(a)). Due to the experiment error, the actual initial dry density (IDD) is 1.54g/cm$^3$, 1.63g/cm$^3$, 1.72g/cm$^3$ and 1.81g/cm$^3$ (Tab.1).

Artificial rainfall system, designed by the Institute of Soil and Water Conservation, Chinese Academy Science, comprises of two spray nozzles, a submersible pump, water box and a bracket. The range of nozzle sizes is 5~12mm, thus, the different rainfall intensity can be simulated. The rain intensity triggering the large-scale debris flow on 21, August, 2011 is 56.5mm/h, which is the designed rainfall for test. The real rainfall intensity is 47~50.2mm/h because the model test is disturbed by the direction of wind. Three groups of sensors, including the micro-pore pressure sensors (the model is TS-HM91) and moisture sensors (the model is SM300), are placed between two layers of the soil to measure the volume water content and the pore water pressure (Fig.2(a)). A data-acquisition system (the model is DL2e) is used to collect the data; it can scan 30 channels within the same second. A camera is used to record the macroscopic process of the entire experiment.

### 2.2.2 Triaxial test

Tests are performed by using a dynamic apparatus in Institute of Mountain Hazards and Environment, Chinese Academy Science. The diameter and the height of sample are 15 cm and 30 cm (Fig.3). Test is the saturated and consolidated drainage shear test at a shear rate of 0.8mm/minute, which comprises of two sets: the initial dry density of 1.94 and 2.00g/cm$^3$. The confining pressure $\sigma_3$ is 50Kpa, 100Kpa and 150Kpa.




(a) Artificial flume model (the position of sampling: red line-1#, pink line-2#, white line-3#) (b) Grain composition of gravel soil

**Fig. 2** Test model and grain composition of gravel soil

**Tab. 1** Sets of artificial flume model test

| Factor / Number | Initial volume moisture content (%) | Slope angle(°) | Rainfall intensity (mm/h) | Initial dry density (g/cm$^3$) |
|---|---|---|---|---|
| 1 | 6~8 | 27 | 47~50.2 | 1.54 |
| 2 | | | | 1.63 |
| 3 | | | | 1.72 |
| 4 | | | | 1.81 |



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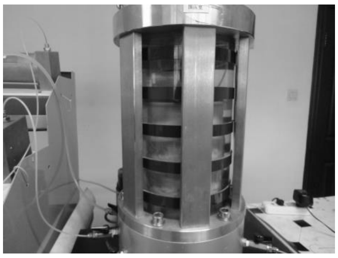

**Fig. 3** Dynamic triaxial apparatus

### 2.2.3 Quantitative analysis method

Quantitative analysis is mainly based on artificial flume model test and triaxial test. Firstly, the state parameters of soil are represented by the void ratio *e* and the mean effective stress *p*′, which are from the model test. In model test, at least three soil samples are collected by soil sampler in the same depth of the line 1#, 2# and 3#, and are used to calculate their natural density $\rho$, mass moisture content $\omega$ and dry density $\rho_d$. Later, *e* can be calculated by the formula: $e=G_s/\rho_d-1$ ($G_s$ is the specific gravity). The cumulative content of coarse $P_5$ (particle diameter > 5mm), gravel (particle diameter < 2mm) $P_2$, and silt and clay (particle diameter < 0.075mm) $P_{0.075}$ is obtained from the particle grading tests. *p*′ can be calculated by the formula: $p'=(\sigma_x+\sigma_y+\sigma_z)/3$, where $\sigma_z=\gamma h$, and $\sigma_x=\sigma_y=K_a\gamma h$. *h* is the vertical distance between a certain point inside the slope and the surface of the slope; $\beta$ is the slope angle, $\gamma$ is the unit weight of soil, $K_a$ is the lateral pressure coefficient, which can be calculated by the formula (1) (Chen et al., 2012). $\phi$ is the internal friction angle of soil. In this paper, $\beta$=27°, $\phi$=33°.

$$K_a=\cos\beta\frac{\cos\beta-\sqrt{\cos^2\beta-\cos^2\phi}}{\cos\beta+\sqrt{\cos^2\beta-\cos^2\phi}} \quad (1)$$

Secondly, the critical state line (CSL) is derived from the triaxial test. Finally, based on the critical state soil mechanics, according to the relative position of the state parameter (*e*, *p*′) at the CSL, the mechanical state of the soil can be estimated. When the soil state (*e*, *p*′) is located at the upper right of the CSL, the soil is contracted. When the soil state (*e*, *p*′) is located at the lower left of the CSL, the soil is dilated (Casagrande A 1936; Schofield and Wroth 1968).

## 3 Results

### 3.1 Macroscopic phenomena of experiment

According to the record by a camera, when IDD is 1.54~1.72g/cm$^3$ except 1.81g/cm$^3$, the landslide can be triggered by rainfall. The processes of the occurrences of landslides have their similarity and difference. The similarity is that at the beginning of rainfall, the shallow soil is compacted by seepage force and soil weight (Fig.4(a)). In addition, during the rainfall duration, surface runoff cannot be observed, whereas muddy water appears and overflows the slope foot (Fig. 4(b)). This phenomenon indicates that the entire rainfall can seep into the internal soil, followed by the formation of subsurface flow. At this moment, the fine particles along the percolation paths begin to move in translation and rotation under the action of gravity (Gao et al., 2011; Igwe 2014) and cause a re-distribution of the microstructure of soil (Chen et al., 2004; Zhuang et al., 2015). These moving fine particles will fill the interval space of porosity, even block the downstream channels of the seepage path (Fang et al., 2012; McKenna et al., 2011), which can lead to a decrease in void ratio and an increase of the pore water pressure (Gao et al., 2011).

The difference of experiment is time and mode of the occurrence of landslide. When IDD is 1.54~1.63g/$cm^3$, the total time of landslide occurrence is 30~40 minutes, including the time of partial sliding and overall sliding. The processes of landslide occurrence involve three steps. Firstly, the partial soil of the superficial layer slowly slides in the shape of mudflow when rainfall duration is about 8min (Fig. 5(a)). Secondly, small-scale slips occur in a layered manner (Fig. 5(b)). Thirdly, the overall sliding is motivated when the rainfall duration is about 33min (Fig. 5(c)). The above processes represent the mode of landslide is the progressive failure. This mode reflects four mechanisms. Firstly, in the early stage of rainfall, the shearing strength of shallow soil decreases and partial sliding appears due to the rapid infiltration of rainfall. Secondly, partial sliding takes away the saturated soil, which causes the internal soil exposed on the surface. Thirdly, the exposed soil slides again, which can change the geometrical shape of the slope and prompt the shearing force increase. Fourthly, when the increase of the shearing force can destroy the balance of the slope, overall sliding will appear.

When IDD is 1.72g/$cm^3$, the total time of landslide occurrence is 18 minutes. Landslide formation process is divided into three steps. Firstly, the shear opening gradually occurs accompanied by the visible cracks developing in the slope foot (Fig. 6(a)). Secondly, surface cracks begin to develop on the slope top (Fig. 6(b)). Finally, landslide initiates accompanied by the instantaneous propagation of cracks (Fig. 6(c)~(d)), which takes 5s. The above steps imply the mode of landslide is the tractive failure. The mechanism includes three aspects. Firstly, an increase in soil weight causes an increase in shearing force, which breaks the equilibrium state of slope, so cracks can develop in the slope foot and cause the shear opening. Secondly, the instability of the slope continues to deteriorate, which leads to new cracks located at the top of the slope. Thirdly, the overall sliding is triggered by crack extension.

When IDD is 1.81g/$cm^3$, the shearing opening appears at the slope foot (Fig. 7(a)). In the next, the muddy water can flow from the slope foot (Fig. 7(b)). Even though on the slope surface, fine particles disappear and coarse particles are exposed, rainfall could not trigger a landslide (Fig. 7(c)). One reason is that the fine particles within the surface soil move with the water seepage. After the fine particles of the shallow soil are all migrated, the soil skeleton begins to consist of coarse particles. This skeleton can provide some smooth paths for the subsurface runoff. The other reason is that when the soil is in a dense state, the change of volume moisture content is limited due to the low permeability. Even if the soil shows a small shearing strain, the loss of pore water pressure is difficult to recover in time due to the lack of rainfall infiltration. Therefore, the shearing strength can remain unchanged.

Macroscopic phenomena of experiments imply that the initial dry density can influence the time and mode of landslide occurrence. It coincides with the existing research (Iverson et al., 2000). As the IDD increases from 1.54g/$cm^3$ to 1.72g/$cm^3$, the failure mode of soil changes from progressive sliding to traction sliding. When IDD is less than 1.63g/$cm^3$, partial sliding is a dominant phenomenon that affects the entire deformation failure. When IDD is 1.72g/$cm^3$, shear opening and cracks are responsible for deformation failure. Although the total time of overall sliding of loose soil is longer than that of relatively dense soil, the time of partial sliding is shorter. This difference may be associated with failure modes, and relative time scales of shearing strength loss and changes of pore water pressure.


**(a) Shallow soil is compacted** **(b) Muddy water is generated**

**Fig. 4 Similarity of process of landslide initiation**

**(a) Soil of the superficial layer slowly slides** **(b) A small-scale slip occurs**

**(c) The overall slide is motivated**

**Fig. 5 Process of landslide initiation (IDD of 1.54~1.63g/cm$^3$)**

**(a) Shearing opening appears in slope foot** **(b) Cracks develop on the slope top**

**(c) Crack propagation** **(d) Landslide is triggered**

**Fig. 6 Process of landslide initiation (IDD of 1.72g/cm$^3$)**



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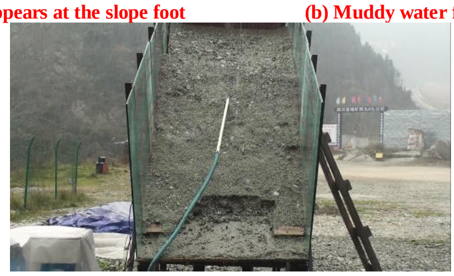
(a) Shearing opening appears at the slope foot

(b) Muddy water flows from the slope foot



(c) Fine particles disappears and coarse particles are exposed

**Fig. 7 Process of experiment (IDD of 1.81g/cm$^3$)**

### 3.2 Volume moisture content (VMC) and pore water pressure (PWP)

The maximum *x* label in Fig.8 ~ Fig.10 represents the total time for the occurrence of the landslide. This value is also the rainfall duration. In order to compare with Fig.8 ~ Fig.10, the maximum *x* label in Fig.11 is 1800s. As shown in Fig.8 to Fig.11, the first change is VMC of the depth of 10cm, followed by VMC of the depth of 25cm and 40cm. This change order of VMC is related to the process of rainfall penetration. Especially, rainfall penetration is from shallow soil to deep soil. Therefore, the VMC of 10cm can increase first. The variation of VMC at the depth of 10~25cm exhibits a similar tendency. The tendency consists of three phases. Since the beginning of rainfall, VMC has been in a constant state. When the rainfall seeps into soil, VMC increases rapidly and eventually grows steadily. The time when VMC of the depth of 10cm begins to increase is 203s, 292s, 313s for 1.54~1.72g/cm$^3$. This result indicates these three densities have different permeability, the higher density, the lower hydraulic conductivity and the longer time of penetration. The time when VMC of the depth of 25cm begins to increase is about 900s for 1.54~1.72g/cm$^3$.

When IDD is 1.54g/cm$^3$ and 1.63g/cm$^3$, VMC at a depth of 40cm initially remains stable and eventually shows an increasing trend. Change trend of 1.54g/cm$^3$ is more obvious than that of 1.63g/cm$^3$. When IDD is 1.72g/cm$^3$, VMC at a depth of 40cm is almost constant. The reason is that when a landslide occurs, rain stops; at this time, no abundant water can penetrate to this depth. When IDD is 1.81g/cm$^3$, if the rainfall duration is less than 1300 seconds, VMC of 40cm remains stable. When the duration is about 1300 seconds, compared to Fig.8 to Fig.10, VMC of 40 cm starts to increase. This difference between Fig.11 and other three figures may be attributed to the following aspect. As mentioned in section 3.1, the landslide cannot be triggered by rainfall. Therefore, there is sufficient time for rainfall to penetrate to a depth of 40cm, although the hydraulic conductivity is low. However, when the rainfall time is greater than 1800 seconds, VMC of 10~40cm keeps constant. This means due to the accumulation of fine particle, there may be an impermeable layer in the depth of 0~10cm. This layer can prevent rain penetrate deeper than 10cm. When rainfall continues, rainfall can be converted into the subsurface runoff, flowing out of the soil skeleton that consists of coarse particles.

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As shown in Fig.8 to Fig.11, PWP at a depth of 10~25cm has a similar tendency. This tendency consists of a sharp increase at first, a rapid decrease and a continuous dynamic fluctuation. However, the variation of PWP is inconsistent with the variation of VMC. Before VMC increases, PWP with the depth of 10cm~25cm has experienced the sharp increase and decrease. Soil inhomogeneity may contribute to this inconsistence. As mentioned in 3.1, at the beginning of experiment, the surface layer less than 10cm is compacted by seepage force and soil weight. The compaction and penetration process leads to the increase of the force acting on the subsoil, which causes the increase of PWP. During the saturation process of the surface layer, the fine particles of this layer are taken away and fill the porosity of the subsoil, which prompt PWP to the peak value quickly. When the surface soil slowly moves or cracks begin to develop in the slope foot, the internal deformation due to dilation will occur, which causes PWP releases. When VMC increases, PWP has a dynamic fluctuation. This fluctuation may be attributed to the rearrangement of the soil skeleton.

The curve of PWP with a depth of 40cm is drawn above that of 10~25cm. The variation has no significant increase or decrease, but exhibits a smooth fluctuation. During the whole rainfall duration, the corresponding VMC shows that the soil is not saturated. Therefore, the pore pressure of 40cm is dominated by air pressure.

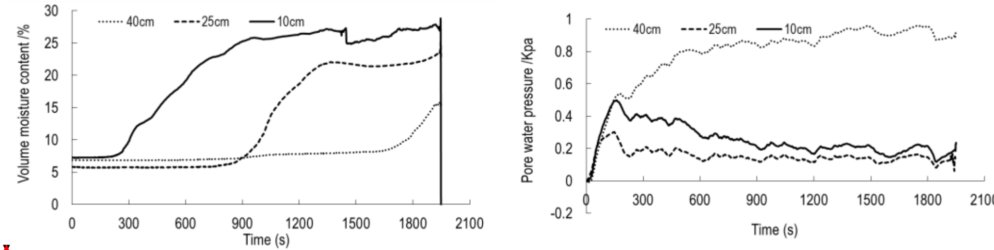


**Fig. 8** Volume moisture content and pore water pressure when IDD is 1.54g/cm$^3$

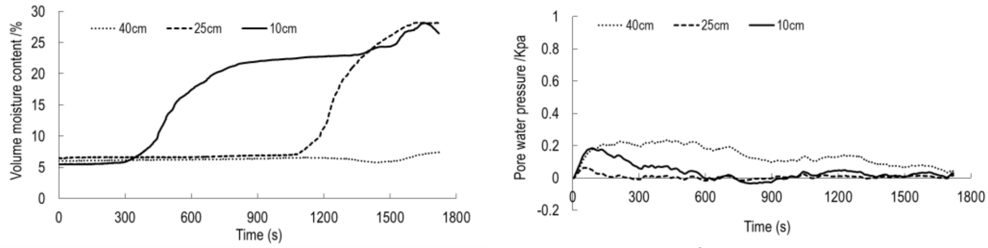


**Fig. 9** Volume moisture content and pore water pressure when IDD is 1.63g/cm$^3$

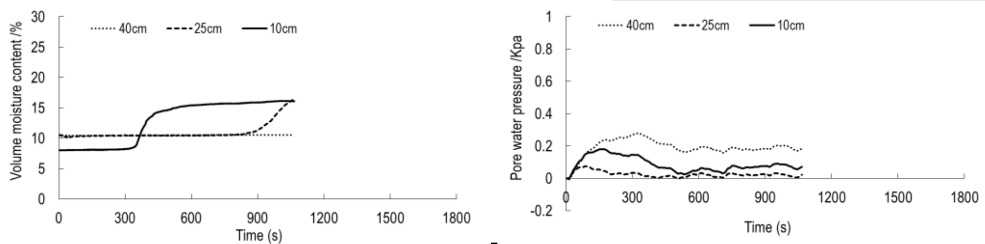


**Fig. 10** Volume moisture content and pore water pressure when IDD is 1.72g/cm$^3$



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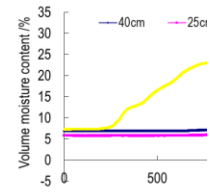

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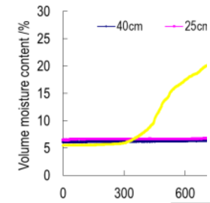

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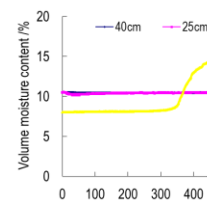

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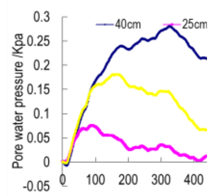

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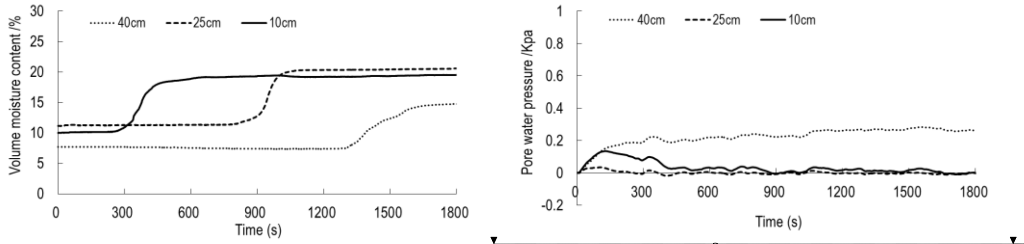



**Fig. 11** Volume moisture content and pore water pressure when IDD is 1.81g/cm$^3$

## 3.3 Microscopic property of gravel soil

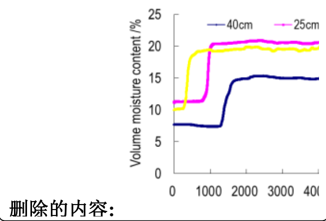
As shown in Tab.2, when IDD is from 1.54 to 1.72g/cm$^3$, the natural density and the dry density with the depth of 5cm~20cm are larger than those before the tests, and the void ratio is less than that before the tests. Of these three lines, the line 1# has the greatest change rate in density. When IDD is 1.63cm$^3$, the density of 40cm is less than the value before the test. When IDD is 1.81g/cm$^3$, the densities with the depth of 5~10cm are increased compared to that before the test.

**Tab 2.** Density and void ratio of gravel soil with initial dry density 1.54~1.81g/cm$^3$

| Number | Initial dry density (g/cm$^3$) | Line number | Soil depth $h$ (cm) | Natural density $\rho$ (g/cm$^3$) | Mass moisture content $\omega$ (%) | Dry density $\rho_d$ (g/cm$^3$) | Void ratio $e=G_s/\rho_d-1$ | $\sigma_z=\gamma h$ (Kpa) | $\sigma_x=\sigma_y=K_a\gamma h$ (Kpa) | $p'=(\sigma_x+\sigma_y+\sigma_z)/3$ (Kpa) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.54 | 3# | 5 | 2.08±0.05 | 9.35±0.85 | 1.90±0.04 | 0.39±0.03 | 1.04 | 0.59 | 0.74 |
| | | 3# | 28 | 1.93±0.03 | 8.61±1.16 | 1.77±0.02 | 0.49±0.02 | 5.39 | 3.07 | 3.84 |
| | | 2# | 33 | 2.07±0.05 | 9.15±0.15 | 1.89±0.04 | 0.40±0.03 | 6.82 | 3.88 | 4.86 |
| | | 1# | 21 | 2.10±0.05 | 9.63±1.01 | 1.91±0.05 | 0.39±0.04 | 4.40 | 2.51 | 3.14 |
| 2 | 1.63 | 3# | 5 | 2.19±0.01 | 13.36±0.09 | 1.98±0.01 | 0.34±0.01 | 0.44 | 0.25 | 0.31 |
| | | 3# | 40 | 1.67±0.03 | 6.15±0.17 | 1.58±0.02 | 0.68±0.02 | 6.68 | 3.80 | 4.76 |
| | | 2# | 20 | 2.09±0.04 | 10.18±0.21 | 1.90±0.04 | 0.39±0.03 | 4.19 | 2.38 | 2.99 |
| | | 1# | 13 | 2.23±0.04 | 10.84±0.83 | 2.01±0.02 | 0.32±0.02 | 2.90 | 1.65 | 2.07 |
| 3 | 1.72 | 3# | 10 | 2.22±0.02 | 8.45±0.72 | 2.05±0.02 | 0.30±0.01 | 2.22 | 1.26 | 1.58 |
| | | 3# | 25 | 2.34±0.04 | 8.59±0.261 | 2.16±0.05 | 0.23±0.03 | 5.86 | 3.33 | 4.17 |
| | | 1# | 10 | 2.30±0.01 | 9.26±0.42 | 2.10±0.01 | 0.26±0.01 | 2.30 | 1.31 | 1.64 |
| 4 | 1.81 | 3# | 5 | 2.14±0.04 | 9.57±0.75 | 1.95±0.04 | 0.36±0.03 | 1.28 | 0.73 | 0.91 |
| | | 3# | 10 | 2.26±0.01 | 8.16±0.39 | 2.09±0.02 | 0.27±0.01 | 2.26 | 1.28 | 1.61 |

As shown on section 2.2.1, $P_5$ before the test is 55.32%. Therefore, coarse particles and fine particles interact to form the soil skeleton, which affects changes in dry density (Guo 1998) and landslide characteristics (Li et al., 2014). In this paper, the particle content before and after the test is compared to understand the change in the void ratio. As shown in Tab.3, when IDD is 1.54g/cm$^3$ and 1.63g/cm$^3$, the loss of $P_{0.075}$ of the shallow soil of line 3# is the largest, followed by that of line 1#. The result indicates that the fine particles of surface soil at the slope top begin to move along direction of gravity firstly. When subsurface runoff forms, these particles begin to move to the slope foot. This process causes two results. One is that the porosity of the position related to particle migration increases. The other is that the porosity filled by fine particles decreases (Fang et al., 2012; McKenna et al., 2011), which is the seepage-compacting effect (Jiang et al., 2013). As a result, the shallow soil of the slope top is looser than that of the slope foot. The loss of $P_{0.075}$ ($\triangle P_{0.075}$, which is negative) at the slope top decreases significantly with depth. Especially, it is about -1.26% at the depth of 40cm. It implies that the depth of rainfall infiltration is about 40 cm. In the case of IDD of 1.72g/cm$^3$~1.81g/cm$^3$, the variation of $P_{0.075}$ of the slope top changes from negative to positive





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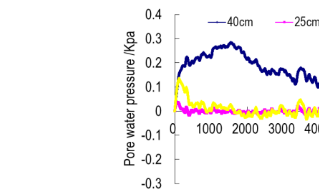

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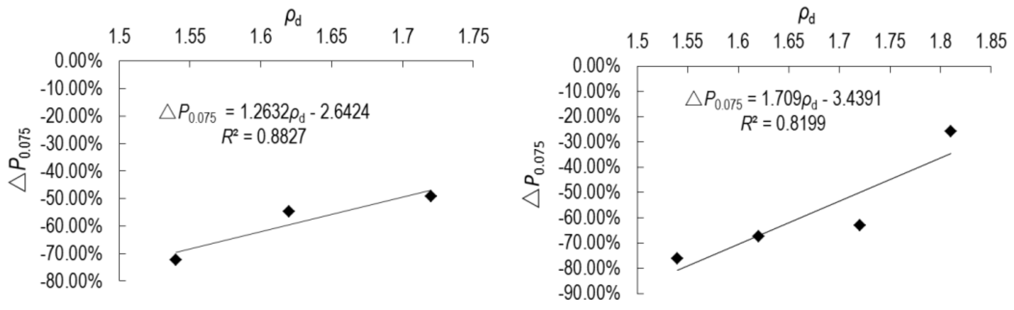
accompanied by the increase of depth. This trend indicates that the fine particles may concentrate at the depth of 5~25cm. The depth range of particle concentration is 10~25cm, 5~10cm for 1.72g/cm$^3$ and 1.81g/cm$^3$.

**Tab 3.** Variation of coarse and fine particles contents

| Number | Initial dry density (g/cm$^3$) | Line number | Soil depth *h* (cm) | $P_5$ | $\Delta P_5$ | $P_{0.075}$ | $\Delta P_{0.075}$ | $P_2$ | $\Delta P_2$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.54 | 3# | 5 | 61.00% | 10.25% | 0.66% | -76.24% | 30.69% | -0.16% |
| | | 3# | 28 | 55.91% | 1.05% | 2.01% | -27.90% | 34.36% | 11.76% |
| | | 1# | 21 | 58.98% | 6.60% | 0.77% | -72.36% | 31.07% | 1.05% |
| 2 | 1.63 | 3# | 5 | 58.69% | 6.09% | 0.91% | -67.23% | 31.40% | 2.15% |
| | | 3# | 40 | 57.98% | 4.80% | 2.75% | -1.26% | 31.69% | 3.07% |
| | | 1# | 13 | 67.66% | 22.30% | 1.26% | -54.81% | 26.23% | -14.68% |
| 3 | 1.72 | 3# | 5 | 55.98% | 1.18% | 1.03% | -62.98% | 32.70% | 6.38% |
| | | 3# | 10 | 54.01% | 2.37% | 1.78% | -36.14% | 33.94% | 10.40% |
| | | 3# | 25 | 55.32% | 0% | 3.17% | 13.85% | 34.05% | 10.75% |
| | | 1# | 10 | 56.15% | 1.5% | 1.42% | -49.09% | 33.67% | 9.53% |
| 4 | 1.81 | 3# | 5 | 52.50% | -5.11% | 2.06% | -25.83% | 35.49% | 15.45% |
| | | 3# | 10 | 52.55% | -5.01% | 2.86% | 2.68% | 33.91% | 10.30% |

Note: the positive value of the change represents an increase while the negative value represents a decrease.

On the slope top, $P_5$ at a depth of 5cm changes from positive to negative with the increasing of IDD, which range is from -5.11% to 10.25%. The reason is that the loss of fine particles contributes to the relatively increase of the content of coarse particles. Both $P_{0.075}$ on the slope top and $P_{0.075}$ on the slope foot decreases. The range of $\triangle P_{0.075}$ is from -25.83% to -76.24% and from -49.09% to -72.36% accordingly. The relationship between $\triangle P_{0.075}$ and $\rho_d$ is shown in Fig.12. The regression equation is as follows: $\triangle P_{0.075}$=1.2632$\rho_d$ - 2.6464, $\triangle P_{0.075}$=1.709$\rho_d$ - 3.4391, and $R^2$ is 0.8827, 0.8199 respectively. The result indicates that $\triangle P_{0.075}$ has a significant correlation with $\rho_d$. Especially, the greater initial dry density causes the smaller loss of $P_{0.075}$. When IDD is 1.53g/cm$^3$, $P_2$ decreases and its change value is -0.16%. When IDD is 1.63~1.81g/cm$^3$, $P_2$ increases, and the range of the change are 2.15%~15.45%. The reason for the loss of $P_{0.075}$ and $P_2$ is that the fine particles are taken away by subsurface runoff. The reason for the increase of $P_2$ maybe that the particles larger than 2mm roll downward, which causes a relative increase in $P_2$.




(a) Slope foot (b) Slope top

**Fig.** 12 Relationship between $\Delta P_{0.075}$ and $\rho_d$



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## 3.4 Critical state of gravel soil

**(1) Definition of critical state and calculation of critical void ratio**

Under the action of continuous shear load, the state of soil is critical when principal stress $q$ and volume strain $\varepsilon_v$ tends to be stable (Casagrande A 1936; Liu et al., 2011; Roscoe et al., 1963; Schofield and Wroth 1968). In the triaxial shear tests, when the axial strain reaches 16%, the deviation stress is stable, and the absolute value of the ratio of $\triangle\varepsilon_v$ to the present $\varepsilon_v$ is less than 0.01; at this time, the soil enters the critical state (Liu et al., 2012). The formula (2) indicates that there is a certain relationship between the current void ratio $e$ and $\varepsilon_v$, wherein $e_0$ is the initial void ratio (Xu et al., 2009). Thus, the critical void ratio $e_c$ also can be calculated by the formula (2).

$$e=(1+e_0)\exp(-\varepsilon_v)-1 \tag{2}$$

**(2) The critical state line in the $e_c$-$p'$ plane**

Tab. 4 shows $e_c$, $q$ and $p'$ for two initial dry densities: 1.94g/cm$^3$ and 2.00g/cm$^3$. As shown in Table 4, when the confining pressure is same, two densities have the approximate similar $e_c$. This result has the consistent principle with existing research (Gabet and Mudd 2006; Iverson et al., 2000). The principle is that the soil with the same granular composition can obtain the approximate critical void ratio in the uniform stress condition (Casagrande A 1936; Roscoe et al., 1963; Schofield and Wroth 1968).

**Tab 4.** Critical void ratio $e_c$ of gravel soil

| Confining pressure $\sigma_3$(Kpa) | Initial dry density (g/cm$^3$) | $e_c$ | $q$ (Kpa) | $p'$ (Kpa) |
|---|---|---|---|---|
| 50 | 1.94 | 0.32 | 93.41 | 95.98 |
| | 2.00 | 0.34 | 69.50 | 84.65 |
| 100 | 1.94 | 0.30 | 227.43 | 213.80 |
| | 2.00 | 0.30 | 159.14 | 178.13 |
| 150 | 1.94 | 0.27 | 324.79 | 312.39 |
| | 2.00 | 0.29 | 181.12 | 239.86 |

The fitting curve of $e_c$ and ln$p'$ is shown in Fig. 13(a). The correlation coefficient is 0.8566, which indicates a statistically significant relationship between $e_c$ and $p'$. According to the normalized residual probability, P-value of 0.964 is greater than the selected significance level, which indicates that the residuals follow a normal distribution. Therefore, the mathematical expression of $e_c$-ln$p'$ of gravel soil is as follows:

$$e_c=0.5241-0.04304\ln p' \tag{3}$$

The fitting cure of $e_c$ and ln$p'$ represents the critical state of soil. It can divide the graphical space into two states. The space above this curve is the contractive zone, and the space below this curve is the dilative zone. If the state parameter ($e$, $p'$) is determined, the soil state can be judged by this line (Gabet and Mudd 2006; Iverson et al., 2000).

**(3) The critical state line in the $q$-$p'$ plane**

The fitting curve of $q$ and the $p'$ is shown in Fig. 13(b). The correlation coefficient is 0.9465, which indicates a statistically significant relationship between $q$ and $p'$. The mathematical expression of $q$- $p'$ is as follows:

$$q=0.6641(p')^{1.063} \tag{4}$$



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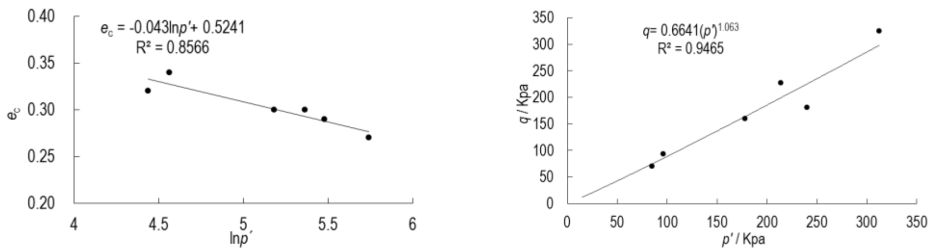


(a) $e_c$-ln$p'$ (b) $q$-$p'$

**Fig.** 13 Critical sate line of gravel soil

## 4 Discussion

The relative position of the state parameter ($e$, $p'$) at the critical state line is shown in Fig.14. The critical states are from Tab.4 and represented by fill dots, and the state parameters of four densities are from Tab.2 and represented by the hollow dots. Fig.14 shows that when IDD is 1.54g/cm$^3$ and 1.63g/cm$^3$, contraction occurs at 28cm and 40cm of line 3#. In addition, dilation appears in the remaining positions. These positions include the surface layer of line 3# with the depth of 5~10cm, the depth of 20~33cm of line 2#, the depth of 10~21cm of line 1#. The results show that dilation and contraction are two types of the mechanical state of gravel soil when the landslide initiates. Dilation is the primary type.

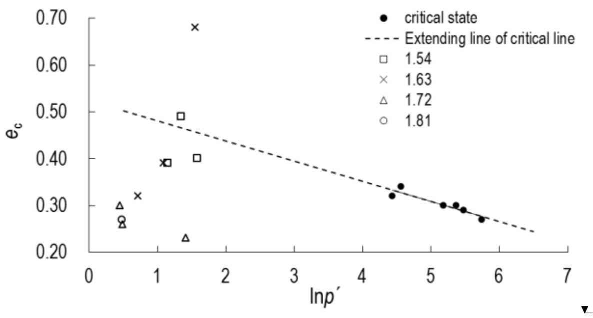


**Fig.**14 The states of gravel soil

In this research, at the beginning of rainfall, the shallow soil is compacted by seepage force and soil weight. The consequent contraction causes the increase in pore water pressure. However, the process of the rapid rise of PWP is short. After PWP reaches the peak, PWP begins to release. The reason is that the surface soil slowly moves or cracks begin to develop in the slope foot, which causes the sliding force increase. Subsequently, the effective stress decreases and the shearing deformation occurs. At this moment, the loss of shearing strength because of strain softening can be restored. Soil deformation will stop eventually. If there is the sufficient water penetration, pore water pressure can recover, and the soil deformation can continue. It can be seen that the loss and recovery of PMP are the reasons for the dynamic fluctuations of PMP. When soil is dense (relative density $D_r$ > 2/3) and the infiltration rate is less than the rainfall intensity, the soil will not reach the critical state. At this point, the slope can remain stable. The macroscopic phenomenon of soil deformation is mainly local deformation, such as circumferential cracks, partial collapse. If the infiltration rate is greater than the rainfall intensity, the abundant rainfall can break the mechanical balance of slope. However, its process still takes a long time. Therefore, the macroscopic deformation is progressive, such as frequent sliding. When the soil is in a medium dense state (1/3<$D_r$≤2/3), the loss of the pore

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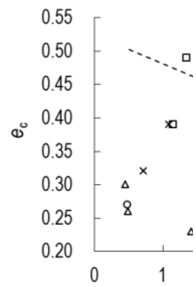

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water pressure due to dilation will be recovered, and the shearing deformation will continue. At this moment, the macroscopic deformation will be a sudden failure (Dai et al., 2000; Dai et al., 1999b).

## 5 Conclusion

(1) The initial dry density can influence the time and mode of landslide occurrence. When IDD is 1.54g/cm$^3$~1.72g/cm$^3$, the failure mode of soil changes from progressive sliding to traction sliding. When IDD is less than 1.63g/cm$^3$, partial sliding is a dominant phenomenon that affects the entire deformation failure. When IDD is 1.72g/cm$^3$, shear opening and cracks are responsible for deformation failure. Although the total time of overall sliding of loose soil is longer than that of relatively dense soil, the time of partial sliding is shorter.

(2) During the experiments, the first change is VMC of the depth of 10cm, followed by VMC of the depth of 25cm and 40cm. The variation of PWP is inconsistent with the variation of VMC.

(3) The occurrence of landslides is accompanied by change in density and void ratio. The slope foot has the greatest change rate in density. The migration of fine particle and the rearrangement of coarse-fine particle contributed to the reorganization of the microscopic structure, which might be the main reason for the variation of density and void ratio.

(4) The mathematical expression of the critical state line of gravel soil is $e_c$=0.5241-0.04304ln$p'$. Mechanical state of gravel soil can be determined by the relative position between the state parameter ($e$, $p'$) and the critical state line. Dilation and contraction are two types of soil state when the landslide initiates. Dilation is the primary type.


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删除的内容: Due to the increase of pore water pressure, the soil of potential sliding surface falls into the shear failure. However, the shearing strain is small. When soil is damagedattributed to shrinkage, the decrease of the porosity leads to an increase of pore water pressure When eivecannot be quickly dissipated in a short time, it can result in contributes to a decrease in the mean effective stress. The whole process of landslide initiation exhibits a sudden fluidization.

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