Characteristics and mechanism of loess landslide induced by drill vibration

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Abstract: In order to reveal the disaster mechanism of loess landslide induced by rig vibration, based on the analysis of typical cases of loess landslide, the disaster process of loess landslide triggered by rig vibration was analyzed through field investigation, physical model test and stress path test. The results showed that the instability mechanism of vibration-type loess landslide was a dynamic process under the action of vibration load. This process can be summarized as follows: stable loess slope -- vibration load of drilling rig -- adjustment of slope stress -- shear failure occurs under continuous load -- slope body begins to slide after sliding surface gradually forms -- landslide forms

1. Introductions
The sand-loess geotechnical zone has successively appeared several landslides during the drilling of oil wells in the Shaanbei Oilfield, and the losses are huge[1,2]. Based on follow-up investigations and analysis, looseness of unsaturated sand loess caused by long-term vibration during oil well drilling and dynamic creep liquefaction of saturated loess, which were the main reason of these landslides. Such ads the sitaimao landslide in zhidan in October 2008, the zoujiagou landslide in qingyang on May 20 in 2009, and the maliancheng landslide in wuqi on August 31 in 2010,[3,4] These landslides not only caused environmental damage, but also directly caused the abandonment of dozens of oil Wells and the damage of drilling equipment, with a loss of tens of millions[5-9].According to follow-up survey, considering these landslides occur before a period of time are not rain, the excavation and pile load is relatively small, drilling fluid leakage is not obvious, some of the sliding zone of landslide is before sliding in the condition of high water content, therefore, that in the process of oil well drilling long vibration effect caused by loose of unsaturated sand loess and saturated loess "creep liquefaction power", is a major cause of the landslide (each landslide wellsite plans to build well 8-10, landslides commonly occurred in 3-4 in construction of Wells, drilling 1 to 2 months already) Loess region of northern shaanxi is an important energy base in China. Hundreds of oil and gas Wells are under construction every year, but due to the limited topography and landform conditions, many of them are located in the slope area where landslides may occur. Therefore, it is of great economic value and social benefit to study the influence of drilling vibration on the stability of the loess slope. In the investigation, it was found that most of these landslides occurred in the sandy loess area, and the sandy loess was easier to loosen and vibrate to liquefy under the dynamic action because of its high sand and low clay, and its properties were quite different from the typical loess and clay loess in the south-southern area. However, there have been few experiments on the dynamic properties of loess in the past. Therefore, it is significance to study the dynamic characteristics of the sand loess under
vibration load and the dynamic response of the slope, in order to perfect the dynamic study of the loess, especially the mechanism of the loess landslide under the action of drilling rig vibration.

Several landslides occurred in the process of drilling oil Wells in loess working area of north shaanxi oilfield. The larger ones include the sitaimao landslide in October 2008, the zoujiagou landslide in qingyang on May 20, 2009, and the MaLiancheng landslide in wuqi on August 31, 2010. There are also many smaller landslides. According to follow-up survey, considering these landslides occur before a period of time are not rain, the excavation and pile load is relatively small, drilling fluid leakage is not obvious, some of the sliding zone of landslide is before sliding in the condition of high water content, in order to analyze the mechanism of landslide hazard, and sums up the common characteristics of the landslide, this article will select the wuqi county Ma Liancheng and huachi zou ditch landslide, the geological conditions and characteristics were respectively in detail, and analyze the mechanism of plague.

2. Regional geology and characteristics of typical drilling vibration landslide

2.1 Regional geology and topography of MaLianCheng landslide in wuqi county

(1) Location and time of the landslide in MaLiancheng, wuqi county

The landslide is located in MaLiancheng village, xuecha town, wuqi county, yan’an city, about 35km away from the county. On August 31, 2008, a large area of landslide suddenly occurred in the 430-30 wells in the wuqi operation area of changqing oilfield, resulting in the abandonment of 1 well under construction and 3 Wells that have been completed, causing huge economic losses. The overall view of the landslide is shown in figure 1, and the platform on the landslide is shown in figure 2.

(2) Morphological and scale characteristics of MaLianCheng landslide in Wuqi county

The plane shape of wuqi landslide is "dustpan shape", with a length of 223m, a width of 249m, a maximum thickness of 50m, and a sliding volume of 1.0 ×10^5 m^3. The overall surface of the landslide is flat and steep in the middle, with an oil drilling platform in the middle and a width of about 50m. Landslide sliding is 77 °, the vertical offset more than 10 m. The upper and lower parts of the landslide are very fragmented.

Field investigation shows that the landslide has obvious faulting characteristics. The concrete performance is that the central platform as a whole goes down lead to drag the upper sliding, and pushing the lower part of the toppling deformation. Landslide sliding process with a large number of cracks in the surface of landslide, the upper of the landslide mass and overall for the are tensile crack, width of 10 ~ 30 cm, and the vertical displacement of the 20 ~ 30 cm, lower part at least 26 cracks, including the shear wall in the front of the crack and ballooning crack, bulge fracture has obvious caricatures characteristic, form a reverse fault, high up to 2 m. The engineering geological plan of the landslide in wuqi MaLiancheng drilling station is shown in Fig. 3.
Fig 3 Engineering geological plan of landslide in wuqi malancheng drilling station

Based on drilling and engineering geology surveying data, the landslide is mainly composed of MaLan loess, local strong weathering newly JiBaoDe group (N2b) mudstone, slide bed is consist of the upper part of MaLan loess and the lower part of the newly JiBaoDe group mudstone (N2b) mudstone. Meanwhile, sliding surface is mainly for the malan loess and mudstone. The engineering geological profile of the landslide in wuqi MaLiancheng drilling station is shown in figure 4.

Fig 4 Engineering geological profile of landslide in wuqi malancheng drilling station

Through the investigation and evaluation, it can be learned that the landslide has occurred sliding, the leading edge of the landslide has reached the valley floor, blocking the valley, because the landslide in a short period of time there is no face, so the possibility of sliding again is not very large. However, the height of the new landslide backwall increased, and the slope becomes steeper after the landslide slide. Meanwhile, the landslide threaten the rural asphalt roads above the backwall of the
2.2 Regional geological survey and geomorphic features of the zoujiagou landslide

(1) Location and occurrence time of the zoujiagou landslide in huachi county

Chen 16-10 well site is located in zoujiagou village, jiangyuan brigade, wujiao town, huachi county, gansu province, which planned to drill 6 Wells, including 1 injection well and 5 production Wells. 3 Wells have been completed and the well construction cycle is 16 days. The fourth well was drilled at 5:00 am on May 20, 2009, and a large-scale landslide occurred at 10:10 am when the drilling reached 65 meters. The derrick on the huachi landslide is shown in figure 5, and the leading edge of the huachi landslide is shown in figure 6.

![Fig 5 Derrick on the zoujiagou landslide in huachi](image)

![Fig 6 The leading edge of the zoujiagou landslide in huachi](image)

(2) The morphological and scale characteristics of the zoujiagou landslide in huachi county

The well site belongs to the leading edge of the loess beam. The south side is limited by large loess gullies, the east is relatively wide and connected with the loess mound. The landslide is distributed on the south side of loess beam and the north bank of gully. The gully is "V" glyph, about 400m wide, groove less than 10 m, narrow groove depth of about 90 m, gully vertical slope, the slope is greater than 80 °, upright local location. There are streams at the bottom of the gully, flood velocity is fast. Meanwhile, gully bed slope is strong erosion bottom, and exposed bedrock. Gully bed bends northward at the landslide, side scour is serious. The engineering geological plan of the landslide in the drilling station of zoujiagou, huachi is shown in figure 7.
FIG 7 Engineering geological plan of the landslide in the drilling station of zoujiagou, huachi

The landslide is a large-scale traction loess landslide, the general trend of east-west, south-leaning, which body is about 500m in east-west width, 70m in height, 200m in maximum thickness and 7.0m ~ 12.0m in slip distance. The middle and rear parts of the slide body are relatively broken, and the front parts are relatively complete except the west side, forming an obvious east-west sag zone in the middle part, which is like a graben, with obvious landslide boundary and sliding drum mound.

There are five gullies extending from south to north, and many tensile cracks and unstable soil on the slide body, and the bottom of the trench is filled by the front edge of the slide body. The estimated sliding volume is over 1,000,000m³.

2.3 Summary of characteristics of drilling vibration loess landslide

The paper analyzes the engineering examples of drilling vibration loess landslide. It is found that most of the drilling vibration loess landslides occur in sandy loess areas, while sandy loess is different from typical loess and clay loess in the south-southern region of northwest China due to its high sand and low clay. It is easier to loosen and vibrate liquefaction under vibration load. The analysis shows that the main causes of the landslide are the loosening of unsaturated sand loess and the rise of pore water pressure of saturated loess caused by the long-term vibration in the drilling process of oil drilling RIGS, as well as the possible problems of "dynamic creep liquefaction".

The landslide of wuqi MaLianCheng drilling station and the landslide of huachi zoujiagou drilling station are listed in this paper as the representatives of drilling vibration type loess landslide in north shaanxi oil field. The characteristics and particularity of these landslide projects are summarized as follows:

(1) The particularity of strata structure features: northern shaanxi loess plateau gully region of the upper stratum structure characteristics is in loess, central as the clay, for sand mudstone, at the bottom of the loess and red clay permeability difference is bigger, easy to form saturated zone in the contact zone, thus reduce the loess strength, slope sliding contact zone along the high water content.
The particularity of physical and mechanical properties of loess in oil fields: loess is characterized by collapsibility, decreased humidification strength, and vibrational liquefaction of saturated sand loess. In addition, because the study area is located in the northern loess plateau, Q$_3$ loess has more sand and less clay. Compared with general loess, it has the characteristics of weak cementation and worse water stability, and the difference in dynamic properties is greater (zhang yongshuang, 2005) [10,11]. In fact, according to investigation of a large number of slopes, we found that the Q2 loess below Q3 in northern shaanxi also has the characteristics of high sand content, so it is called sand loess.

3. Instability influence factors and mechanism of the loess slope

3.1 factors influencing the instability of the loess slope in the oilfield area

There are many factors that influence the slope instability in the oil field, but they can be summarized into two aspects: one is the natural environmental conditions, the other is the man-made engineering activities. The formation of a landslide alway the result from several factors, and one or several of them play a major role, landslide research try to find out the dominant factors, in order to treat the symptoms of the respective prevention and treatment, but also should not completely ignore the impact of other factors.

1. The natural factors of slope instability in oilfield work area

(1) Geological background factors. There are a large number landslides in the loess plateau area. The geological background of the landslides is mainly as follows:

① The intermittent and differential rise of tectonic movement, the corresponding river cutting and erosion, as well as the later loess accumulation, form a high and steep slope shape, providing topographic conditions for the landslide.

② Under the loess layer with loose, permeable and vertical joints, there are weak "easy to follow strata", such as red clay layer and sand shale.

(2) Groundwater. The action of groundwater, including wetting and softening, static or dynamic water pressure, erosion etc. It is a necessary condition for landslides. Soil layers have the characteristics of softening and greatly reducing strength when exposed to water, especially for weak soil, which is prone to physical weathering and chemical dissolution, thus becoming the primary factor leading to landslides. In addition, the moisture content of the slope soil increases gradually, which increases the dead weight of the sliding body, and at the same time increases the hydraulic gradient. The combined effect of these factors is very unfavorable to the slope stability.

(3) River erosion. The lateral erosion and cutting of the river have a great influence on the stability of the slope. The study area is located in the uplift state as a whole, with strong cutting action of the river, large drop ratio of the river valley, large fluctuation of the flood, strong erosion of the foot of the mountain slope and the front edge of the landslide, easy to produce new landslides and induce the revival of old landslides. Several large landslides occurred recently in the oil field, such as the landslide of dalougou oil transfer station, the landslide of huachi Chen 16-10 well site and the landslide of yan103 well site, are all related to the erosion of the river.

(4) Atmospheric precipitation. Groundwater level is inducement of landslides, and meteoric water is an important source of groundwater recharge, so there are many landslides in continuous rainfall or rainstorm season, especially in areas with annual rainfall over 50mm. Due to the crack water, water often become the trigger factor of the landslide development.

(5) Earthquake. Earthquake is often the trigger of landslides, landslides caused by the earthquake is not winless .The 1920 haiyuan earthquake in TianShui, it has produced a lot of collapse, landslides...

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and loess liquefaction flat push landslide is proof. There are many seismic cracks in loess area, which indicates that earthquake has great influence on slope stability.

2. The engineering activity factors of slope instability in oilfield area

   (1) Slope excavation. In the construction of oil Wells, stations and roads, a large amount of excavation and slope cutting is inevitable, which leads to the change of the original stress field and stress state of the slope, especially when the slope is steep or when the original supporting part of the slope is cut off, the traction landslide is often formed.

   (2) Loading of fill, dump, machinery and building. Heap loads, such as fill, pile up abandoned soil or mechanical loads, are carried out on the upper and rear edges of the slope. These loads will increase the sliding force of the slope, thus generating a push-type landslide.

   (3) Leakage of construction water. Water is needed in the process of drilling in oil field. Although anti-seepage measures are adopted, seepage is inevitable. Therefore, it may increase the severity of the sliding body, weaken the strength of the rock and soil body, and thus reduce the stability of the slope body.

   (4) Engineering vibration. In the process of oil well construction, the vibration of the derrick, drill string and so on is very significant, resonance occurs in some cases, coupled with the long drilling time, the slope may accumulate deformation under dynamic load, thus gradually evolving into a landslide. In addition, such as a well site in FanXue, the generator set is placed on the edge of the slope, and the long-time vibration leads to the slope collapse, which threatens the safety of the well site.

3.2 Genetic mechanism of loess landslide in oilfield

The genetic mechanism of loess landslide in oilfield area includes natural landslide genetic mechanism and engineering landslide genetic mechanism. The genetic mechanism of natural landslide includes: 1. Landslide mechanism in rainy season (heavy rain and long-term rain); 2. Mechanism of freeze-thaw landslide; 3. Third, damage accumulation and progressive landslide mechanism. The genetic mechanism of engineering landslide includes: 1. Engineering excavation unloading landslide mechanism; 2. Mechanism of engineering overburden landslide; 3. Mechanism of engineering water accumulation, water leakage and landslide; 4. Mechanism of engineering vibration landslide.

Wuqi landslide is the key research object. According to the regional geological survey and topographic and geomorphic characteristics of the landslide, the analysis showed that the occurrence mechanism of the landslide is as follows:

(1) Old structures form ancient terrains. Field investigations in the downstream of the landslide is located in valleys found 1 the small fault, for the normal fault, to about 150 °. Landslide is located on the upper wall of the fault. Due to the presence of faults, the sedimentary thickness of mudstone on both sides of gully varies greatly. The thickness of the mudstone revealed by #5 borehole has reached 36.5m, and the underlying cretaceous huachi formation sand mudstone (K2h) has not yet appeared. Meanwhile, the footwall mudstone has good integrity and stratified structure, while the hanging wall mudstone is relatively broken. Due to the fact that the erosion resistance of the sand and mudstone of the cretaceous huachi formation is far greater than the Neogene jibaode (N3b) mudstone, the ancient landform where the landslide located in low-lying, and the later quaternary deposits are also thicker.

(2) Neotectonics shape modern terrain. There is a typical "valley in valley" landscape in the valley where the landslide is located. The change of Neotectonics movement can be inferred from the geomorphologic landscape. It can be inferred that in the early and middle Pleistocene, the region was in a rapid uplift movement, resulting in the absence of surface Q1 and Q2 strata and steep surface slope. In late Pleistocene, the uplifting movement slowed down, showing a gentle landform in the middle of the slope. Since the holocene, it has been in rapid uplift movement, with strong surface cutting erosion and steep surface slope. The landform left on the earth's surface is step-like slope surface, and the convex slope formed is very disadvantageous to the stability of the slope.

(3) Modern surface-erosion slopes appear to face three empty Spaces. Under the effect of
Neotectonic movement, the surface of downward erosion is very strong. The gully incline 30° to 45°, local can reach 60° ~ 70°. The Malan loess at the bottom of the gully was eroded away and the upper part of the loess was exposed to the sky. In addition, the formation and development of the gully on the north side of the landslide resulted in the planar convex landform where the landslide was located.

(4) The trailing edge tension of the gravity action formula. Due to the aerial action of the front edge of the landslide, under the action of gravity, the tensile stress concentration is generated at the back edge of the landslide, and the loess is very low, which is easy to form tensile cracks. Tensile cracks reduce the strength of soil, and they provide a good path for surface water injection.

(5) The infiltration of surface water reduces the strength of the soil. The surface water is injected through the infiltration of the sliding body and the crack at the rear edge, which increases the water content in the sliding body. At the same time, due to the water-separating effect of the sliding bed, a saturated zone is formed, which promotes the formation of the sliding belt.

(6) Gravity and engineering loading accelerate the formation of sliding surfaces. Under long-term gravity and additional load, the upper part of the landslide is gradually cut off, and plastic shear failure occurs at the lower part.

Wuqi landslide was influenced by many factors, among which human engineering activities play an important role in the process of landslide formation. According to our follow-up survey, considering the landslide occurrence for a period of time before there were no rain, the excavation and pile load is relatively small, drilling fluid leakage is not obvious, before sliding of the landslide sliding zone which is in a state of high water content, therefore, that in the process of oil well drilling long vibration effect caused by loose of unsaturated sand loess and the pore water pressure of saturated loess, saturated loess and the possible existence of "dynamic creep liquefaction", is one of the main causes of the landslide (wuqi landslide wellsite plans to build well 8-10, the landslide occurred in 3 Wells construction, drilling nearly 2 months already). Therefore, this paper only studies the mechanism of engineering vibration landslide in depth.

Oil drilling is carried out on the loess slope, a platform is usually dug on the slope and drilling is carried out on the platform, as shown in figure 9. Vibration in the process of oil well construction is different from earthquake and general artificial vibration. Due to the generally large depth of oil and gas well mining, fast drilling speed, complex drilling equipment and strong power, high vibration frequency and large amplitude variation, it had become non-negligible factor disasters. Oil well drilling process, the vibration of the derrick, the drill string is very significant, and because of long time drilling, accumulation of excessive deformation can also lead to slope instability, the other in some special cases, the drill string, derrick will happen resonance, greatly increasing the vibration amplitude, not only threaten the safety of drilling equipment, the stability of the slope will be greatly reduced.
According to the analysis and the previous research, it is concluded that due to the large depth of oil wells, the required drilling equipment has high quality, strong power and complex operation, and the vibration effect in the drilling process is very obvious. The failure forms of the loess slope are various under the vibration load of oil drilling rig. The displacement, pore pressure rise, and vibration liquefaction of the slope are the manifestations under the vibration action of the "long duration, medium and high frequency" drilling rig base.

4. Conclusions

According to the previous description of the dynamic characteristics of the loess in the oil field, the analysis of drilling vibration parameters and the calculation of the dynamic response of the slope the instability mechanism of the loess slope under the action of the construction vibration of oil field drilling RIGS can be summarized as follows:

1. Vibration damage and subsidence of loess in the middle and upper part of slope. In the upper part of the loess water content is low, in power for a long time under the action of cementation damage, injury, damage to further expand, destroyed the structural loess, the loess in the big pore structure gradually destroyed, particle size is less than 0.075 mm of silt under dynamic load, moving to the surrounding than their size relatively large pores, so that the soil will become compacted, generating the residual strain, and the residual strain increases with the continuation of construction load vibration time, so the loess slope body vibration load in construction, such as drilling, dynamic compaction, etc.), the gradually accumulated deformation, and then the collapse occurs.

2. The pore water content of saturated (high water content) loess in deep slope rises. Although the vibration load of the deep soil is relatively small due to the attenuation of vibration, the long duration of vibration leads to the accumulation of deformation, and the pore water pressure gradually increases and the strength decreases.

3. Formation and expansion of sliding surfaces. With the continuous application of dynamic load in oil rig construction, the strain of slope body gradually accumulates, and at the same time, the range of soil liquefaction also increases, and the stress state of slope is adjusted accordingly under the continuous action of vibration load. Shear failure occurs when the shear stress is greater than the maximum shear strength of soil under the vibration load of oil drilling rig construction. Under the continuous action of the vibration load of drilling machine, the structure and strength of the soil mass after shear failure are further damaged. Then the stress inside the slope mass is redistributed, and the failure area gradually develops towards the potential sliding surface inside the slope mass. With the continuous expansion of the scope of the failure soil mass, the sliding surface will penetrate the whole slope mass.

4. The high-speed sliding of a landslide. When the sliding surface completely penetrates the whole slope, the sliding force will be far greater than the anti-sliding force of the sliding surface. Meanwhile, the sliding body will slide down rapidly along the sliding surface under the action of dead weight and vibration load of oil drilling rig.

To sum up, the instability mechanism of vibration-type loess landslide is a dynamic process under the action of vibration load in oil rig construction. It can be summarized as follows: stable loess slope -- vibration load of drilling rig -- adjustment of slope stress imbalance -- shear failure occurs under continuous load -- slope body begins to slide after sliding surface gradually forms -- landslide forms.

At first, the paper selected the representative of the wuqi and huachi landslide, the general situation of the regional geological drilling vibration model of the loess landslide and landform characteristics made a detailed introduction. The vibration type characteristics of loess landslides are summarized. Vibration model of the loess landslide influence factors of instability and mechanism are analyzed. It is concluded that engineering vibration is an important factor for slope instability in oil field, and the mechanism of engineering vibration landslide is briefly expounded, which provides the factual and theoretical basis. Construction for oilfield drilling vibration characteristics are analyzed in theory, because of the lack of effective test methods and equipment, so did not drill on the engineering practice of construction vibration for the actual test, and ultimately relatively realistic theoretical
analysis, dynamic triaxial test and numerical simulation. Finally, the instability mechanism of loess landslide under the action of oil rig vibration is analyzed and summarized, and the following conclusions are obtained:

1. The instability mechanism of the loess slope under the vibration of oil drilling rig is studied deeply, and it is considered that the vibration of oil drilling rig is also an important factor to trigger the loess landslide. According to the analysis, the failure forms of the loess slope under the vibration load of oil drilling rig are various, the displacement and the rise of pore pressure and the vibration liquefaction of the slope under the vibration action of the "long-duration, medium-high frequency" drilling rig base are the main forms. It can provide scientific basis for landslide risk control in oil well construction in loess area of north shaanxi oilfield.

2. On the vibration characteristics of oil rig drilling process and on the slope along the horizontal and vertical direction the propagation law of analysis research, in oilfield drill in drilling engineering, longitudinal, transverse and torsional vibration is throughout, which is the interaction and influence, its vibration order is: longitudinal vibration > transverse vibration > torsional vibration.

3. The instability mechanism of loess landslide is a dynamic process under vibration load in oil rig construction. This process can be summarized as follows: stable loess slope -- vibration load of drilling rig -- slope stress adjustment -- shear failure -- slope body begins to slide after sliding surface gradually forms -- landslide

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