# Mechanism and Control of Subgrade Mud Pumping Under the Cyclic Load of Train

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**Abstract**. Railway subgrade mud pumping is one of the most common defects. Unfavorable combination of soil, water, dynamic load is the main cause of subgrade mud pumping. Based on the source of water causing railway subgrade mud pumping, it can be divided into 5 major categories; on the basis of three stages forming mud pumping, the defect mechanisms are explored and the influencing factors are analyzed; identifying the defect categories is the premise of determining railway subgrade rehabilitation schemes, while geological radar detection is proved to be an effective mean appropriate for railway mud pumping detection; common mud pumping prevention measures are concluded, so as to provide references for the railway subgrade mud pumping defect controlling project.

## Introduction

Railway sleeper failure, steel rail direction deviation, uneven surface, folding and a series defects brought by railway subgrade mud pumping have intensified the impact of train wheels on rails, thus seriously affecting the rail structure and directly endangering the traffic safety[1]. Meanwhile, mud pumping has reduced the stiffness of the rail bed, where mud is mixed with ballast, resulting in uneven rail bed stiffness and uneven stress on rail pillow which is easy to fracture. Also the steel rail wear is large; in winter, when the mud becomes dry, the upper layer of rail bed is stiff which has lost the elasticity, so the dynamic effect of train increases as well, resulting in the increase of foundation bed stress and further destroying the foundation bearing stratum, also set a dangerous precedent for the future [2, 3]. In recent years, with the development of China's railway transportation industry, particularly under situation of the speed increase on railway, rapid development of heave load train and increasing transport volume, the disaster of railway subgrade mud pumping is becoming more seriously [4].

## Categories of Mud Pumping

Mud pumping is divided into the type of track bed and the type of foundation bed. Track bed mud pumping means that when the ballast is dirtied, mud is squeezed to pump out under the dynamic load of train, as is shown in Fig.1. Foundation mud pumping means that soil foundation or weathered rock foundation is eroded and softened by water, therefore resulting in liquefaction into mud so as to be squeezed and pumped under the dynamic load of train, which causes permanent deformation of the subgrade. Track bed mud pumping is related with foundation bed mud pumping. As a result of development of track bed mud pumping, it will cause foundation bed mud pumping. Once the ballast is polluted and crashed into powder, it will lead to the poor permeability causing the track bed hardened, where water will be easily accumulated in the center of subgrade resulting in foundation bed mud pumping. Fig.2 is the typical characteristics of railway subgrade mud pumping.

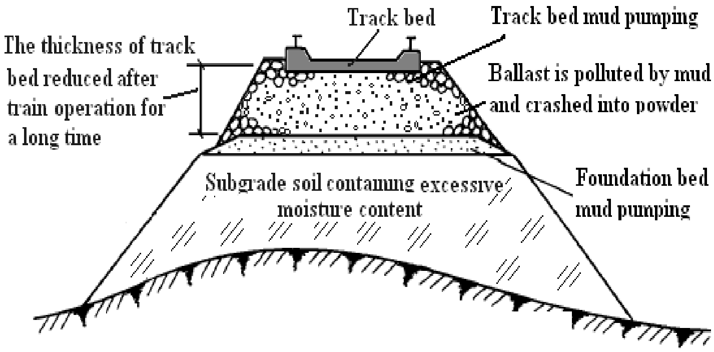


Fig. 1 Example of Track Bed Mud Pumping Fig. 2 Typical Characteristics of the Mud Pumping

Based on situation of subgrade bed soil, mud pumping can be divided into 4 categories: ①Soil-based mud pumping, commonly seen on the embankment and soil cutting with no ground water or section with poor ground water development. ②Batholith mud pumping. The subgrade consists of mud soft rock, where mud pumping happens in actions of rain water, live load and ballast grinding. ③Fissure spring mud pumping, mostly takes places in cutting of mountainous and hilly areas or sections with developed groundwater. ④Subsidence squeezing, the subgrade soil presents a soft plastic state to be extruded towards the slopes or side ditches.

According to the source of water causing mud pumping, it can be divided into five types: ①Groundwater: Affected by ground water, the soil base is often wet which results in mud pumping. ②Surface water: Affected by surface water, the soil base is moisture which will cause mud pumping. Surface water mainly refers to seasonal rainwater accumulation, also including surface seepage water due to the poor road drainage. ③Moisture water: Due to rainy in construction or embankment filled with the soil containing excessive moisture content, which significantly increases the water content of upper part of embankment under the effect of subzero temperature so as to cause mud pumping. ④Gaseous water: Under the action of strong temperature difference in winter, water in soil will move up in gas state and accumulate in the top embankment and pavement structure, so that mud pumping occurs. ⑤Type of mixed water: Mud pumping occurs under synthetic action of the above of two water types.

## Mechanism of Mud Pumping

There are many channels developed in mud pumping effected sections of the railway embankment, referred to as “mud-pumping channel.” Under the dynamic load of train, pumping and capillary action are significantly in mud pumping concentration areas. Due to the softened road bed, mud going through the track bed after raining is a reflection of mud pumping channel centered distribution [5, 6]. In investigations of existing lines, the developed forms and degree of mud pumping channels are extremely complex, which can take various forms, mostly with the shape of small top and big bottom cones.

Studies have generally believed that the mud pumping of subgrade is the fine ingredients in soil transit with water [7, 8]. Sufficient conditions for occurrence of the mud pumping are: ①Abundant fine ingredient in embankment soils; ②Fine sand is missing in ballast with the existing channels of mud pumping; ③Existing Free water; ④Existing the recycling load. When a train passes, due to the action of impact load, railway sleeper is pressed down, and the excessive pore water pressure increases as well; after the train passes, railway sleeper suddenly restores to the normal position, which leads to the pumping of fine-grained soil in the bed and thus the forming mud pumping phenomenon [9, 10]. In short, the disadvantageous effect combination of soil, water and dynamic load is the key of mud pumping generation in subgrade beds.

According to the observed mud pumping states during excavation and train running, current studies group the formation of mud pumping into three stages: squeezing and uprising stage, mud extrusion and suction stage, and mud pumping formation stage.

### Squeezing and Uprising Stage

After the completion or overhaul of railway, the ballast is clean with even surface and smooth drainage, and therefore mud pumping is less likely to happen. However, with the extending of operation time, since hydrophilic clay or easily weathered hydrophilic soft rock is paved on the subgrade, under cyclic loading of train, uneven sedimentation would generate on the surface of subgrade bed. Once rainfall infiltrates into, water will accumulate in the lower, while the accumulated water is difficult to remove causing by low permeability coefficient of clay of the subgrade. Ballast interacts repeatedly with the compacted soil so that it is loosened and softened to form mud. Mud rises up along with the hole of ballast, which is the primary stage of mud pumping formation. If continuous rainfall happens in this stage, the muddy zone would be formed continuously of the subgrade soil, and the mud in ballast would be squeezed to rise. Once with no sufficient water supply, the mud level will stop to rise and dry after a period of time, and finally harden the ballast. In this stage, mud will not be squeezed out of the ballast bed generally.

### Mud Extrusion and Suction Stage

The hardened ballast layer formed in the first stage is not very dense, which would also generate shrinkage cracks during dry period. Once rain water infiltrates into the subgrade bed during the rainy season, the hardened layer will mud again. In course of mud rising, the mud is under two actions. One is squeezing stress, and the other is suction stress. Causes of the two stresses is the mud ballast layer has formed a relatively close hardened layer, which increases the mud pressure in pores of ballast bed under outside load, so that the compressed mud outbursts from pores and cracks in parts of the hardened layer with weak cementation to cause the rise of harden layer. Suction effect is forming during this stage because the hardened ballast layer vibrates up and down under the cyclic load of train. When the hardened lay rises, the place on subgrade bed surface would form vacuum belts under the sleeper, which could suck the surrounding water and mud into them. Once the hardened layer is pressed down, water pressure in the pores and cracks will increase leading to the mud level rise. This is the second stage of mud pumping formed by extrusion and suction.

### Mud Pumping Formation Stage

With the rain infiltration, subgrade bed is softened, and mud is squeezed and sucked to rise repeatedly, so that the ballast hardened is increasingly serious. Sealing effect of the hard shell is more and more obvious, resulting in pore water pressure generation and accumulation. The pressured mud could still rise up along some pores and cracks out of the hardened ballast layer, and covers the railway sleeper, which makes mud accumulate above the ballast with weed growing. After the mud pumping formed and happens again, it can be divided into small recycling mud pumping, large recycling mud pumping and integrated mud pumping three types according to the degree.

## Influencing Factors of Mud Pumping

Subgrade mud pumping is the result of comprehensive actions from soil, water, temperature, cyclic load and many other factors. Among them, soil, water, and temperature are internal conditions and train load is the external factor forming subgrade mud pumping.①Subgrade filler. In general, coarse grained soil is less likely to cause the mud pumping, because the height of capillary rise is small with less ice, and can maintain a certain degree of strength in saturated state. But silt and clay content in the coarse exceeds a certain amount, the frost heaving increases significantly, which can also form the subgrade mud pumping. ②Water. Water is the main factor causing roadbed defects. The essence of subgrade mud pumping is the process of water migration and phase transition. Surface water infiltrating the soil of subgrade will reduce the shear strength, thus causing various defects; groundwater increases the moisture content of subgrade soil in cohesive soil and mud rock, and reduces the shear strength as a result. Under train load as well as other external forces, more serious mud pumping and other defects will occur. ③Temperature. The impact of temperature mainly reflects in frost damage on subgrade. Without a certain frost depth or freezing index, it is difficult to form frost heaving or subgrade mud pumping. Changes in temperature mainly cause water migration and phase transition, therefore resulting in mud pumping. With respect to water, temperature is an indirect factor. ④Cyclic load. Mud pumping is indispensable with the cyclic load of train. Dynamic stress of train load generated on subgrade is huge, but its horizontal and vertical distributions are uneven. Generally, the train load is closely related to axle load, train speed, sleeper technical condition, and etc. It is considered that within certain range of traffic volume, the volume and the generation of subgrade mud pumping is almost a linearly proportional relationship.

## Mud Pumping Defect Detection

The range of railway subgrade defect is broader with various degrees. In order to propose targeted regulating measures, it is required to explore the defected degrees of each section. Exploration drilling, excavation and light dynamic penetration test ($N_{10}$) are traditional methods. Although traditional exploration drilling is direct, the effect is poor and consuming in time and labor. Moreover, it will damage the lines, while only information of local points can be reflected which cannot accurately master the comprehensive information of the whole line subgrade. In addition, exploration drilling method cannot detect the defect in-depth situation of subgrades along rail lines. The information provided by construction excavation is lagging, which is adverse to the determination of defect regulation range and reasonable arrangement of regulation process. $N_{10}$ tests are more applied in reality, but the information reflected is not enough, too.

Geological radar detection is a non-contact detection method suitable for the detection of railway subgrade[11]. Practice shows that the geological radar can quickly and continuously detect the railway subgrade without damage but of high accuracy. It not only gives hierarchical structure under the defected section, vertical exploration along the line can also distinguish differences among various vertical sections, and also be able to offer each tested section required to improve and the specific types of mud pumping, so as to provide basis for the regulation design[12]. However, excavation is still an essential testing and auxiliary means for physical prospecting as geological radar detection.

## Control Measure of Mud Pumping

For mud pumping prevention, principles as "Prevention first, combining prevention with regulation" should be taken. At present, remedy of the foundation bed mud pumping costs 10~100 times more than the type of track bed. Thus, it is very important to distinguish the categories of mud pumping and confirm the length of defect line. It is the key of deciding the whole regulation scheme.

Basic approach to remedy mud pumping are: ① Arrange subgrade drainage system, adjust subgrade temperature conditions and prevent surface water, groundwater or other moisture entering into the upper subgrade. For example, isolation layer and heat isolation layer should be set in the subgrade, improve subgrade drainage, increase subgrade height and so on. ② If there is water accumulated in the upper subgrade, then the excessive moisture should be removed timely during freeze-thawing or temporarily stored in the pavement structure layer with good permeability and water stability, such as setting geosynthetics or sand cushion to drainage water. ③ Improve subgrade and strengthen the road surface, like subgrade soil replacement or reinforced soil application; limestone soil, cinder limestone soil and other structural layer. ④ In some cases when applying only one measure cannot achieve expected effect or not economic or reasonable enough, integrated measures of two or more than two measures can be applied.

Common subgrade mud pumping regulations methods are shown in Table.1. In actual engineering, in order to achieve ideal remedy effects and reduce labor intensity, while reducing the interference in traffic, comprehensive measures of two or more than two are usually adopted.

Tab. 1 Subgrade Mud Pumping Prevention Measures and Scope of Application

| Measure No. | Measure Type | Pumping type | Pumping degree | Applied regions or conditions | Note |
|---|---|---|---|---|---|
| 1 | Subgrade drainage | ①; ②; ⑤ | Light, medium, heavy | Plains, hilly area, mountainous area | Applied in both new and old subgrades |
| 2 | Increasing the subgrade height | ①; ②; ⑤ | Light, medium, heavy | Plains, depressions, basins | Applied in both new and old subgrades, can be combined with any of the 3rd to 9th measures when necessary |
| 3 | Sand (gravel) cushion | ①; ②; ③; ⑤ | Medium, heavy | Sand and gravel production areas | Applied in both new and old subgrades, mainly used as cushion, can be combined with the 2nd or 4th measures |
| 4 | Lime soil structural layer | ①; ②; ③; ④; ⑤ | Light, medium, heavy | Lack of sand and gravel areas | Applied in both new and old subgrades, mainly used as f- oundation or cushion, can be combined with the 3rd or 5th measures |
| 5 | Cinder lime structural layer | ①; ②; ③; ④; ⑤ | Medium, heavy | Lack of sand, stone area with guaranteed cinder supply | Applied in both new and old subgrades, mainly used as foundation or cushion, can be combined with the 4th measures |
| 6 | Permeable isolation layer | ①; ②; ⑤ | Medium, heavy | Sand and stone production area | Applied in new subgrades |
| 7 | Impermeable isolation layer | ①; ②; ④; ⑤ | Medium, heavy | Asphalt, felt paper, pla- stic film with guarante- ed impermeable geote- xtile supply areas | Mostly applied in new subgrades |
| 8 | Blind ditch | ①; ⑤ | Light, medium, heavy | Hill side or transverse ground water exposed section, section with high ground water level | Applied in both new and old subgrades |
| 9 | Soil replacement | ①; ②; ③; ⑤ | Medium, heavy | Material areas with gravel production or good stability | Applied in both new and old subgrades |

Note: ①; ②; ③; ④; ⑤ refer to the number of mud pumping categories in this paper based on the difference of water source.

## Conclusion

Railway subgrade mud pumping is one of the most common defects, while the adverse effect combination of train load, water and soil is the main cause of mud pumping generation. Essentially, mud pumping is the transition process of fine particles with water. Based on the difference of water source causing mud pumping, it is divided into 5 categories in this paper, and common treatment measures for different types of mud pumping are given as well. According to the different stages of mud pumping formation, its mechanism is explored and the affecting factors are analyzed. Geological radar detection is an effective measure to identify and recognize the type of railway subgrade mud pumping. Applicability of various treatment measures for mud pumping are compared to offer references for railway subgrade mud pumping disease control.

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