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SINKING OF HILL ROAD DUE TO GRAVITATIONAL DEFORMATION AND RATE OF SINKING AT PAGLAJHORA SINKING ZONE IN DARJEELING HIMALAYA IN INDIA

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1. INTRODUCTION

Landslide hazard management of hill roads is critically needed in India due to its severe natural conditions[1)]. Among such hazards, gradual sinking of hill roads is one of the major problems in India especially in the Himalayas, where hill roads run through steep hill slopes. Landslides may be blamed for the sinking but, if "landslide" means repeated mass movement on gentle slope with landslide clay on slip surface, it may not be charged for most cases of the sinking in the Himalayas.

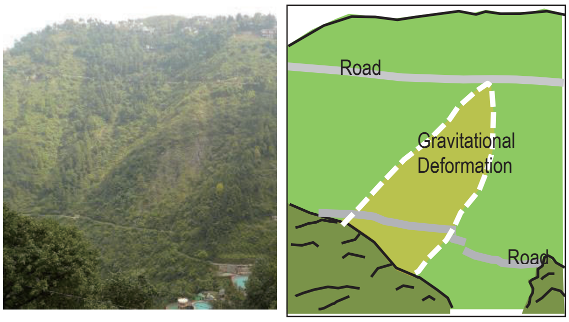


Figure 1 Gravitational Deformation and Sinking of Hill Road in Uttarkhand, India[2)]

In a technical cooperation project in India funded by JICA, Capacity Development Project on Highways in Mountainous Regions, we proposed gravitational deformation be blamed for many sinking sections in the Himalayas[2)], as shown in Figure 1. Gravitational deformation often involves slope failures and rock fall at its toe and flanks as the deformation proceeds.

In this paper, we estimate rates of sinking at road by gravitational deformation.

2. GRAVITATIONAL DEFORMATION

Gravitational deformation, or creep deformation, of steep hill slope has been well studied in Europe. Crosta summarized various studies relating to deep seated gravitational deformation[3)]. In Japan, deep-seated catastrophic landslides were triggered by Typhoon 12 Talas in 2011, which highlighted gravitational deformation as a precursor of such disasters[4)]. After the typhoon, studies of gravitational deformation have been extensively conducted.

(1) Difference between Landslide with Clay on Slip Surface and Gravitational Deformation

Table 1 shows difference between gravitational deformation and landslide with clay on slip surface.

Table 1 Landslide with Clay on Slip Surface and Gravitational Deformation[2)]

Item	Landslide with Clay on Slip Surface	Gravitational Deformation
Slope	**Gentle slope** <= 30 degrees	**Steep slope** 30 degrees <=
Boundary between moving & stable parts	Slip surfaces with thin sheared zone of landslide clay,	Loosened zone of fractured bedrock
Thickness of the boundary	Several ten centimeters.	Several meters.
Movement mode	Slide on slip surface	Creep deformation of loosened zones
Groundwater involved	Pore water pressure on slip surface	Pressured fissure water

In this paper, the word "landslide with clay on slip surface" means repeated mass movement on gentle slopes with landslide clay on slip surface. Such landslides also cause sinking of roads in hilly regions.

(2) Topographic and Geological Features

Gravitational deformation often shows particular topographic features on the slope where it lies. Such features are well studied so far. Gianfranco organized geomorphological features of gravitational deformation in Italian Alps, which focuses uphill facing scarp on the shoulder and bulging at the toe of the slope5).

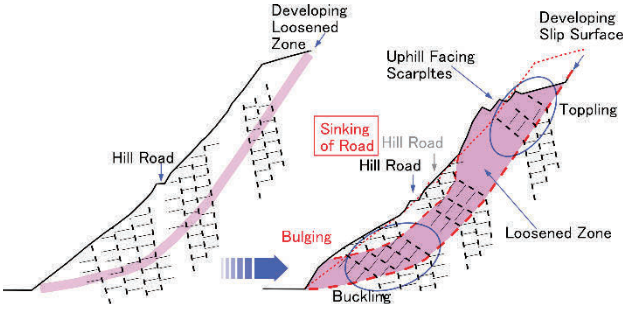


Figure 2 Development of Gravitational deformation2)

Gravitational deformation also involves loosened zones of fractured bedrock, where bedrock creep proceeds with toppling at the shoulder and buckling at the middle and toe as shown in Figure 2. The loosened zones often form water passage for fissure water. At the toe of slopes where loosened zones appear to the surface, groundwater spring / seepage are often observed.

(3) Mechanism of Gravitational Deformation & Sinking of Hill Roads

Gianfranco reported slow and continuous sagging and bulging of valley slope profile due to gravitational deformation5), which supports the sinking of hill roads due to the same. At bulging, however, hill roads may be uplifted instead.

Gravitational deformation often starts from relaxation of hill slope due to unloading or stress relief. Along with relaxation, facilitated by fractured zones of bedrock, loosened zones develop underground mainly parallel with slope surface as well as at the flanks of deformation blocks. In loosened zones, bedrock creep proceeds slowly but steadily and downward deformation of a block follows, which results in sinking of hill loads2). In several decades, sinking of hill roads by gravitational deformation may reach a height of several tens meters, such as shown in Figure 2.

(4) Gravitational Deformation to Deep-seated Landslide

Gravitational deformation is considered as a precursor of a deep-seated catastrophic landslide6)7). The mechanism of causing a deep-seated catastrophic landslide is still being discussed, however.

Triggering a deep-seated catastrophic landslide may require strong force to destabilize large parts of a bedrock slope. Figure 3 shows a possible process of generating pressured fissure water strong enough to cause such landslide2):

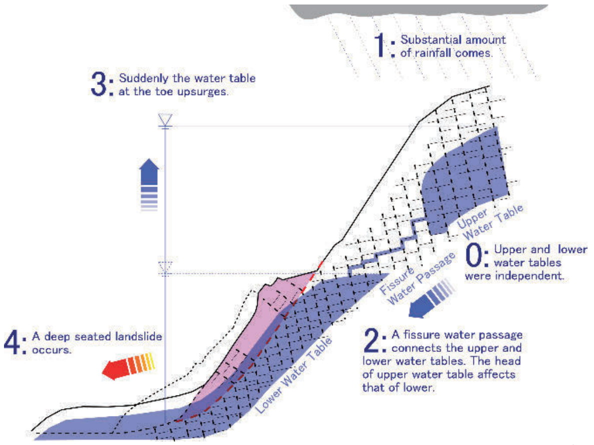


Figure 3 Possible Mechanism of Deep-seated Landslide2)

a) The lower water table formed by fissure water behind a gravitational deformation slope is independent from the upper one, which may lie in upper slope far behind the lower one.
b) Due to abundant provision of water to the fissure in upper slope by substantial rainfall, a fissure water passage connects the upper and lower water tables. Then the head of the upper affects the lower.
c) The head of the lower water table at the toe of the slope drastically surges, up to the head of the upper one less resistance loss.
d) A deep-seated catastrophic landslide is triggered by such strong water pressure.

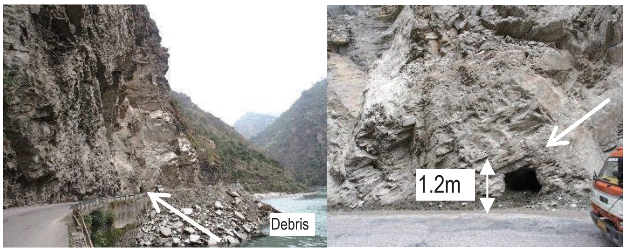


Figure 4 Peculiar Hole with Groundwater at the toe of slope

In India, along hill roads in the Himalayas, deep-seated landslides / collapse involving bed rock are often observed with devastating damage to roads. A massive rock collapse in 2015 at a section of Kulu - Manali Highway (NH21) supports the proposed process in Figure 3. As shown in Figure 4, a large peculiar hole with ground water spring was observed at the toe of the rock slope, which corresponds to the plane of rupture of the rock collapse. The large hole at the toe is thought to be made by the strong water pressure triggered by the connection of the upper and lower water tables behind the slope when the collapse occurred.

Kosugi suggested effects of water tables in the ridge of hill slope to those at the toe8), which is favorable to the aforementioned proposed process.

3. PAGLAJHORA SINKING ZONE

National Highway NH55 in West Bengal in India connects Darjeeling, the famous tourist destination, to Siliguri, the major town of the strategic Siliguri Corridor. From Sukna to Kurseong, NH55 climbs up a height of around 1,400 meters within a stretch of 40 km. A famous sinking zone of Paglajhora lies before Kurseong.

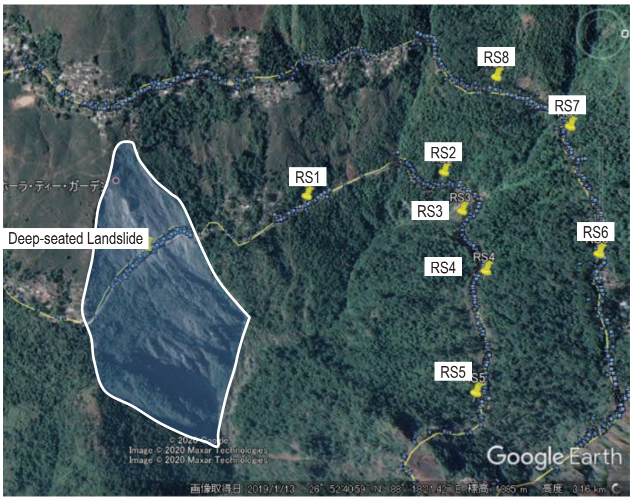


Figure 5 Deep-seated Landslide and Road Sinking in Paglajhora

The activities of Paglajhora Sinking Zone have decade's long history. Sujit Mandal summarized comprehensive review of the zone, in which subsidence of roads were reported 9).

Paglajhora Sinking Zone includes a trace of a massive catastrophic deep-seated landslide and road sinking sections. Through a study in February 2020, 8 road sinking sections were confirmed as shown in Figure 5.

(1) Geological Condition

Geology of the Indian Himalayas is composed of 4 geological zones stretching east and west, among which Greater Himalayan Sequence underlies Paglajhora Sinking Zone. Greater Himalayan Sequence is composed of highly metamorphic rock of gneiss, migmatite, and quartzite10).

The slopes in Paglajhora Sinking Zone are very steep with average gradients of 60 ~70 degrees9).

(2) Map Reading

Aerial photo reading is an effective way for detecting topographic features relating to landslides. Aerial photos are, however, difficult to obtain in India. In the project, instead, map reading was performed to detect such topographic features, with contour maps generated by a GIS with spacial information obtained by satellites, as explained in Table 2.

Table 2 Contour Map Preparation

Item	Description
GIS	QGIS Ver.2.18
Satellite Image Data	DEMs from "ALOS World 3D-30m (AW3D30)" provided from JAXA, Japan Aerospace Exploration Agency

Through map reading, blocks of gravitational deformation are interpreted by extracting topographic features of the deformation2). Figure 6 shows a result of map reading for the site. The 8 road sinking sections in Figure 5 correspond to the gravitational deformation blocks interpreted through map reading.

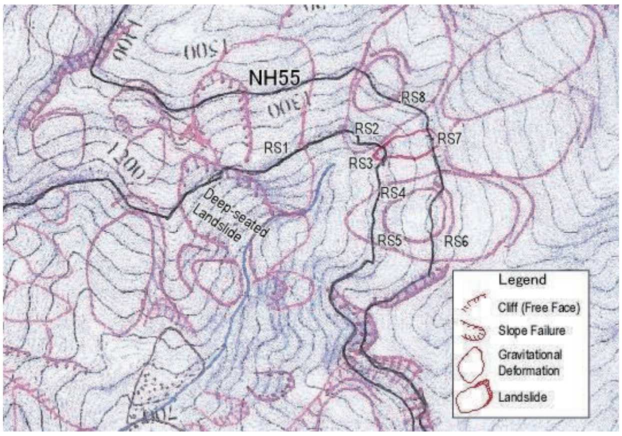


Figure 6 Map Reading of Paglajhora Sinking Zone

(3) Deep-seated Landslide

The massive deep-seated landslide occurred in the rainy season in 2010, which further developed in 2011 by Sikkim earthquake9). The Sikkim earthquake totally demolished NH55 and the rail track of Darjeeling Himalayan Railway (DHR) including their foundations.

After a long repairing period, NH55 and DHR opened again in 2015~16, crossing the trace of the deep-seated landslide.

Interestingly, a peculiar hole similar to that of Figure 4 was reported at the trace of the deep-seated landslide11). It is thought to be made by the strong water pressure explained in Figure 3 as well.

At the trace of the deep-seated landslide, gravitational deformation is developing in the form of three layers with bending and sinking of NH55 and the railway track of DHR at the boundaries among the layers.

Figure 7 [2)] explains the deformation in three layers. Bending and sinking of NH55 and the railway track of DHR have been observed as shown in Figure 8 [2)].

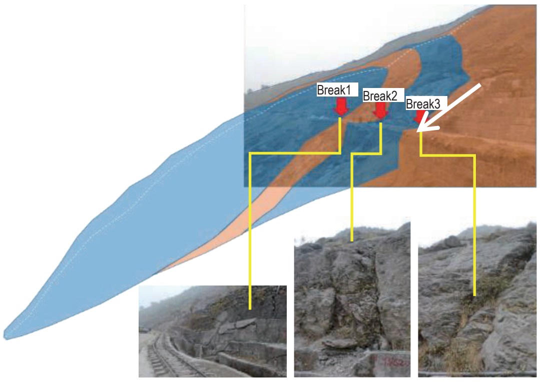


Figure 7 Gravitational Deformation in Layered Structure [2)]

Figure 8 Deep-seated Landslide (Left) and Bending and Sinking of Highway and Railway Track (Right) in 2017 [2)]

(4) Road Sinking Sections

In the monsoon season in 2010, along with the deep-seated landslide, damage to NH55 occurred at several locations [9)].

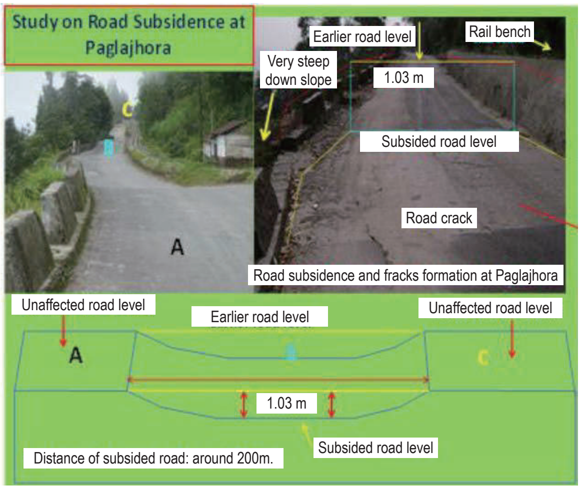
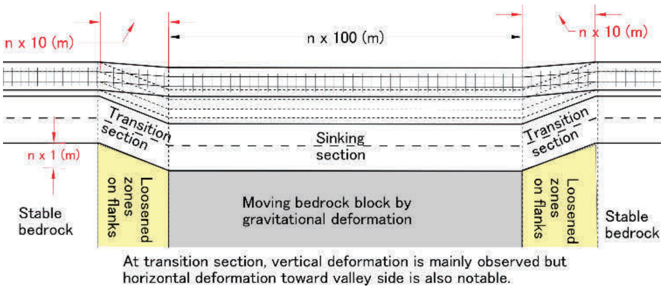


Figure 9 Road Sinking at RS1 in 2009 [9)]

Before the deep-seated landslide in 2010, the road sinking at RS1 was recorded as 1.03 meters in 2009, as shown in Figure 9 [9)]. Sujit Mandal reported other records of sinking as 6 ~ 8 meters, 1.42 meters, and 0.95 meters/year, the exact locations of which are, however, unclear [9)].

(5) Typical Form of Road Sinking

A typical form of road sinking in Paglajhora Sinking Zone is explained in Figure 10.



At transition section, vertical deformation is mainly observed but horizontal deformation toward valley side is also notable.

Figure 10 Typical Form of Road Sinking in Paglajhora (no scale)

A sinking section often has transition sections on both sides at the boundaries with neighboring stable sections. Sometimes it is found only on one side. By comparing the map reading result in Figure 6 and the actual site conditions, it is understood that the transition sections correspond to the loosened zones at flanks of the gravitational deformation blocks.

In Paglajhora Sinking Zone, the railway track of DHR is often filled up to keep its vertical gradient gentler than the steepest limit for operation, whereas that of NH55 often remains unchanged as long as vehicles can run over the transition sections.

4. SINKING RATE AT ROAD

(1) Gravitational Deformation at Deep-seated Landslide

At the gravitational deformation at the deep-seated landslide in Paglajhora, photographs of sinking at the fixed location are available, which enable us to estimate the rough rate of road sinking.

The photos in 2016 are shown in Figure 11.

Figure 11 Photos in May (Left) and August (Right) in 2016

The photos in Figure 12 are in 2018 and 2020.

Figure 12 February 2018 (Left) and February 2020 (Right)

The photo in May 2016 in Figure 11 is right after the reopening of NH55 and DHR and that in August 2016 is during the first monsoon after the reopening.

Figure 13 Raised Railway Track of DHR (H=20cm)

By comparing the photos in 2016, 2018, and 2020, development of sinking is well understood, especially by the deformation of the retaining wall placed on hill side along the railway track.

As shown in Figure 13, the foundation of the railway track was found partially broken in February 2020, through which abandoned railway track was found. The raised height is 20cm. From the situation, the abandoned track should be the one in the reopening in 2016 and the raised one should be laid before February 2018. The minimum rate of sinking is, therefore, estimated as 10 cm / year or more.

On the other hand, by comparing the photos in 2018 and 2020 in Figure 12, focusing on the top lines of the retaining wall indicated by the white lines, the rate of sinking in two years is roughly estimated as around 10 cm /year or more. Thus rough rates of sinking at Paglajhora deep-seated landslide may be around 10 cm / year or more.

(2) Road Sinking Section RS1

RS1 has a typical transition section where vertical alignment of NH55 drastically changes.

Figure 14 Transition Section of RS1 (2020)

At the transition section, as the downward movement of gravitational deformation proceeds, horizontal alignment of NH55 is also pushed to valley side, as shown in Figure 14.

At RS1, as shown in Figure 15, an abandoned road was found on the valley side, which connects to the current NH55 at the boundary with the stable section, as shown in Figure 14 on the right.

By comparing the photos in 2020 in Figure 15 with that in 2009 in Figure 9, rough estimation of a rate of road sinking is possible. From Figure 15, the height between the railway track of DHR and old NH55 is estimated to be around 2.7 meters. (The man in the photo is 180cm tall). The difference between the stable and sinking section in Figure 9 is roughly 1.0 meters. Thus the amount of sinking from 2009 to 2020 is around 1.7 m, which leads an estimated sinking rate of around 15 cm / year.

Figure 15 Height Difference between Old and New NH55 (2020)

(3) Road Sinking Section RS4

At RS4, at least 2 layers of abandoned roads were found along the current NH55 as shown in Figure 16.

Figure 16 Abandoned Road of NH55 at RS4

The height from the lowest abandoned road to the current NH55 is around 3.6 meters. Unfortunately, we have no certain data when the lowest road started sinking. The volume of sinking estimated from the abandoned road is of noteworthy, however.

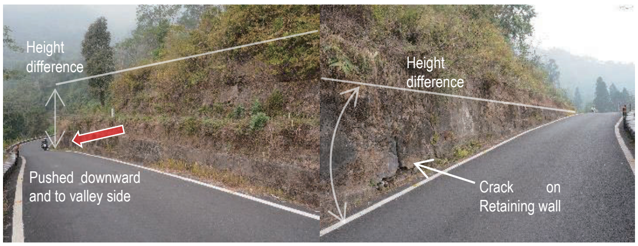


Figure 17 Transition Section on East End of RS4

Similar to the volume of sinking, as shown in Figure 17, the height difference at the transition section on the east end is also large. Cracks on the retaining wall along the road are often observed, along with horizontal deformation toward valley side.

5. Discussion

The estimated rates of sinking at hill road sections in Paglajhora are 10 cm/year or more and 15 cm/year.

These estimation may be considered as an average value through a period of several years. An actual rate of sinking may vary between monsoon and dry seasons, through which precipitation and groundwater conditions should vary. Further study is needed to understand behaviour of road sinking over seasons and its relation with amounts of precipitation or groundwater conditions.

In addition, the proposed mechanism of road sinking caused by gravitational deformation requires verification through further studies. In the project, the following surveys are planned in a similar gravitational deformation site:

- Core boring
- Subsurface displacement / groundwater / rainfall monitoring
- Resistivity survey in rainy and dry seasons
- Slope stability analysis

Based on the results from the above listed, the mechanism of sinking will be reviewed and appropriate countermeasures against sinking of hill road will be proposed.

The estimated sinking rates need to be reviewed with more records of sinking. Considering the fact that NH55 has kept its service after the reopening in 2016, however, the rate of road sinking should fall in the range which enable the road authority to maintain NH55 with daily maintenance works, such as filling crack, partial repaving, and easing displacement at transition sections. The estimated sinking rates of 10 cm/year or more and 15 cm/year fall in such range.

6. Conclusion

Through the studies at Paglajhora Sinking Zone in Darjeeling Himalaya in India, the following findings are understood or confirmed:

- Along the hill road running through steep hills/mountains, road sinking is often caused by gravitational deformation of bedrock.
- Road sinking by gravitational deformation often has a transition section which lies between sinking and stable sections.
- Transition section corresponds to the flank of gravitational deformation block, where loosened zones develop underground.
- The estimated rates of sinking at road sections in Paglajhora Sinking Zone are 10 cm/year or more and 15 cm/year.
- The maximum road sinking confirmed in the study in February 2020 by comparing the abundant and current NH55 is around 3.6 meters.

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