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Hill Slope Erosion due to River Meandering and its Retrofitting- A Case Study

Satyendra Mittal[1], Sonam Ladol[1], Nehul Tyagi[1], Sangeeta Singh[2]
[1]Indian Institute of Technology (IIT) Roorkee, India
satyendramittal@gmail.com; civiliansonam@gmail.com; tnehul@gmail.com
[2]S.S.D.P.C. Girls (PG) College, Roorkee, INDIA
drsangeetasingh22@gmail.com

Abstract- At one site in Himachal Pradesh state of India, one landslide occurred in recent past which caused total wash away of road, sliding of huge soil mass, deposition of loose material towards river flow, reduction of water way of river flowing in valley etc. The main reason of this hill slope landslide was toe erosion of slope due to meandering of river at that location. The landslide at this location is an annual feature in every monsoon: The authors did an extensive survey to this site and noted that the river below in the valley eroded the toe of hill slope due to meandering at that location. Due to toe erosion, the state highway also washes away every year, which causes a huge revenue loss to the state. Authors have developed the permanent solution to this problem by designing spurs, groynes, rigid pavement (with ground improvement measures) and hill slope stabilization through anchors.

***Keywords*:** Soil erosion, retrofitting, meandering, ground improvement, landslide, stabilisation

1. Introduction

Himalayan range is generally termed as young mountains. Landslides are natural calamities in fragile Himalayas. In Paonta Sahib (HP), near Kacchi Dhang, landslides occurred in recent past which caused total wash away of road, sliding of huge soil mass, deposition of loose material on d/s side of road towards river, reduction of water way of river flowing in valley etc. The local people confirmed that total washing away of road is almost an annual feature there between ch. 15 + 300 to 15 + 580. Hence it was decided to take up work of stabilization of hill slopes on top priority by HP govt. and Ministry of road transport, Govt. of India.

2. Soil Strata at Site

The soil present at site is close to silty sand. Following soil parameters were suitably taken for the sake of analysis. (Table 1):

Table 1: Soil Parameters

Soil Parameters	Value
Avg. Cohesion (c) kPa	0
Angle of shearing resistance (ϕ) in consolidation stage	330
(c) Unit weight of soil (γd)max	17kN/m3
γsat	19.9kN/m3
(d) Moisture Content	17%
(e) Angle of internal friction (Ø)	22

3. Design of Rigid Pavement

The proposed highway was facing landslides in every monsoon season since last 5 years at this location. Due to that, the road was washed away every year. Therefore, it was recommended to provide a rigid pavement. The design of rigid pavement has been done according to IRC: 58, 2015.

Design Data

Traffic Data: 1000 CVPD (in one direction)

Subgrade support

(a) Soaked CBR value (Natural/Host soil) = 7.0%, (b) Design Period = 30 Years, (c) Growth rate of traffic = 0.075 (7.5 percent)

3.1. Selection of Modulus of Subgrade Reaction

For the design of M-40 grade concrete to achieve modulus of rupture of at least 4.5 MPa, the strength of the subgrade is expressed in terms of modulus of subgrade reaction (k), which is determined by plate load test at the subgrade level.

IRC: 58, 2015 has suggested a correlation between the soaked CBR and k value of the subgrade for homogenous soil subgrade as presented in Table 2.

Table 2: Correlation between CBR & K-value

Soaked CBR, %	2	3	4	5	7	10	15	20	50	100
k-value, MPa/m	21	28	35	42	48	55	62	69	140	220

k- value of subgrade (MPa/m)	21	28	42	48	55	62
Effective k-value for 100mm DLC, MPa/m	56	97	166	208	278	300
Effective k-value for 150mm DLC, MPa/m	97	138	208	277	300	300

3.2. Design of Pavement Section

Selection of Flexural Strength of Concrete For heavy traffic, the characteristics flexural strength of concrete shall not be less than 4.5 MPa as specified in accordance with MORTH Fifth Revision. Therefore, M40 grade concrete is recommended for the present design. The following design stipulations are assumed for the design of rigid pavement:

Characteristics compressive strength of concrete at 28 days = 40 MPa

90 days compressive strength of cement concrete = 48 MPa

Characteristics flexural strength of concrete at 28 days = 4.5 MPa

Flexural strength of concrete 90 days = 4.95 MPa

3.3. Design analysis for Fatigue Analysis

Design Period = 30 years

Rate of traffic growth (r) = 0.075 (7.5 %)

Cumulative repetitions in 30 years

Commercial traffic volume per day = 1000 cvpd in (one direction)

$$\mathbf{C} = \frac{\mathbf{365 * A\{(1 + r)^{n} - 1)\}}}{\mathbf{r}} \quad (1)$$

Where,

C = Cumulative no. of CVs during the design period

A = Initial No. of CVs per day in the year when the road is opened to traffic

R = Annual rate of growth of CT volume
n = Design period in years
$C = \frac{365*1000\{(1+0.075)^{30}-1)\}}{0.075}$ = 37740782 CVs
Total 2-way commercial vehicles during design period = 75481564

Taking the average number of axles (steering, single, tandem and tridem) per commercial vehicle as 2.35 (IRC: 58-2015), total two-way axle load repetitions during the design period of 30 years would be = 7581564 x 2.35 = 177,381,675 standard axles.

3.4 Design Traffic for Fatigue Analysis

In the current design, 100 percent standard axles have been considered without giving due consideration of 25 percent of the total repetitions of commercial vehicles as a special case for the given site situation.

It is assumed that 40 percent of the commercial vehicles travel during night hours (6PM to 6AM).

Therefore, night time (12 hour) design axle repetitions =177,381,675 x 0.40
=70,952,670

Day time (12 hour) design axle repetitions = 177,381,675 x 0.60 axles
=106,429,005

Day time (6 hour) axle load repetitions = 106429005/2 axles =53,214,502 axles

Therefore, design number of axle load repetitions for bottom-up cracking analysis would be 53214502 axles.

Night time (6 hour) design axle repetitions = 70,952,670/2 = 35476335 axles.

3.5 Fatigue Damage Analyses

Effective modulus of subgrade reaction (k) =208 MPa/m
Elastic modulus of concrete (E) = 30,000 MPa
Poisson's Ratio of concrete (μ) = 0.15
Unit weight of Concrete (γ) = 24 kN/m3
Design flexural strength of concrete = 4.95 MPa

Maximum day time temperature differential in slab for bottom-up cracking (BUC) for the state of Himachal= 13.1° C for 200 mm slab thickness (as per IRC code)

Night time temperature differential in slab for top-down cracking (TDC) would be

$$\frac{\textbf{Day time difference}}{\mathbf{2}} + \mathbf{5} \qquad (2)$$

=12.15°C

Let us consider concrete pavement with tied concrete shoulders with dowel bars across transverse joints.

Let us assume the trial thickness of 23 cm (h = 0.23 m). The radius of relative stiffness, l is calculated using the equation

$$\mathbf{l} = \left[\frac{\mathbf{EH^3}}{\mathbf{12(1+\mu^2)^k}}\right]^{\mathbf{0.25}} \qquad (3)$$

$$l = \left[\frac{30000(0.23)^3}{12k(1+\mu^2)}\right]^{0.25}$$

$$= 0.6219\text{m}$$

The total fatigue damage (for Bottom-up cracking) for single rear axle load of 100 kN and pavement with tied concrete shoulders.

Maximum tensile stress at bottom of the slab would be
For k=208

$$\mathbf{S = 0.042 + 3.26\left(\frac{24 * 0.23^2}{208 * 0.6219^2}\right) + 1.62 * \left(\frac{Ph}{kl^4}\right) + 0.0522 * \Delta T} \qquad (4)$$

S = 1.974 Mpa

The stress ratio = 1.974/4.95 = 0.398 < 0.45 (IRC:58-2015) (Clause :5.8.6)

Therefore, the concrete is expected to sustain infinite number of repetitions. Hence, no fatigue damage is checked. The assumed slab thickness 23 cm is safe against fatigue damage.

3.6. Expressions for Maximum Tensile Stress at the Bottom of the Slab (for Bottom-up Cracking Case) are as follows as per IRC:58-2015

Single axle-Pavement with tied concrete shoulders

a) $K \leq 80$ MPa/m
$S = 0.008 - 6.12\ (\gamma h^2/k/^2) + 2.36\ Ph/(k/^4) + 0.0266\ \Delta T$ .... (i)

b) $K > 80$ MPa/m, $k \leq 150$ MPa/m
$S = 0.08 - 9.69\ (\gamma h^2/k/^2) + 2.09\ Ph/(k/^4) + 0.0409\ \Delta T$ .... (ii)

c) $K > 150$ MPa/m
$S = 0.042 + 3.26\ (\gamma h^2/k/^2) + 1.62\ Ph/(k/^4) + 0.0522\ \Delta T$ .... (iii)

Single axle-Pavement without concrete shoulders

a) $K \leq 80$ MPa/m
$S = 0.149 - 2.60\ (\gamma h^2/k/^2) + 3.13\ Ph/(k/^4) + 0.0297\ \Delta T$ .... (iv)

b) $K > 80$ MPa/m, $k \leq 150$ MPa/m
$S = 0.119 - 2.99\ (\gamma h^2/k/^2) + 2.78\ Ph/(k/^4) + 0.0456\ \Delta T$ .... (v)

c) $K > 150$ MPa/m
$S = 0.238 + 7.02\ (\gamma h^2/k/^2) + 2.41\ Ph/(k/^4) + 0.0585\ \Delta T$ .... (vi)

Tandem axle-Pavement with tied concrete shoulders

a) $K \leq 80$ MPa/m
$S = -0.188 + 0.93\ (\gamma h^2/k/^2) + 1.025\ Ph/(k/^4) + 0.0207\ \Delta T$ .... (vii)

b) $K > 80$ MPa/m, $k \leq 150$ MPa/m
$S = -0.174 + 1.21\ (\gamma h^2/k/^2) + 0.87\ Ph/(k/^4) + 0.0364\ \Delta T$ .... (viii)

c) $K > 150$ MPa/m
$S = -0.210 + 3.88\ (\gamma h^2/k/^2) + 0.73\ Ph/(k/^4) + 0.0506\ \Delta T$ .... (ix)

Tandem axle-Pavement without concrete shoulders

a) $K \leq 80$ MPa/m
$S = -0.223 + 2.73\ (\gamma h^2/k/^2) + 1.335\ Ph/(k/^4) + 0.0229\ \Delta T$ .... (x)

b) $K > 80$ MPa/m, $k \leq 150$ MPa/m
$S = -0.276 + 5.78\ (\gamma h^2/k/^2) + 1.14\ Ph/(k/^4) + 0.0404\ \Delta T$ .... (xi)

c) $K > 150$ MPa/m
$S = -0.3 + 9.88\ (\gamma h^2/k/^2) + 0.965\ Ph/(k/^4) + 0.0543\ \Delta T$ .... (xii)

The following table (Table 3) shows the fatigue damage for 23 cm slab thickness

Table 3: Fatigue Damage due to Bottom-up Cracking

H (m)	γ kN/m3	K (MPa/m)	P KN)	ΔT °	Stress MPa	Stress Ratio	Allowable repetitions	Fatigue Damage
0.23	24	208	100	13.1	1.974	0.398	Infinite	-

Therefore, a slab thickness of 23cm is adequate for the consideration of Bottom-up Cracking
Similar analysis is done for top-down cracking and the results are given in Table 4.

Table 4: Fatigue Damage due to Top-down Cracking

H (m)	γ kN/m3	K (MPa/m)	P KN)	ΔT °	Stress MPa	Stress Ratio	Allowable repetitions	Fatigue Damage
0.23	24	208	100	12.15	2.0375	0.414	Infinite	-

Since, the value of stress ratio (0.414) is less than 0.45, the road slab thickness assumed as 0.23m is OK.

4 Design of Revetment and Launching Apron

- Launching apron shall be provided for the protection of toe and it shall form a continuous flexible cover over the slope of the possible scour hole in continuation of pitching up to the point of deepest scour. The stone in the apron shall be designed to launch along the slope of the scour hole to provide a strong layer that may prevent further scooping out of river bed material.
- The size and shape of apron depends upon the size of stone, thickness of launched apron, the depth of scour and the slope of launched apron
- At the junction of slope pitching with launching apron, a toe wall shall be provided as shown in fig, so that pitching does not rest directly on the apron. It will protect the slope pitching from falling during the launching of apron even when the apron is not laid at low water level
- Design Flood discharge Q = 6028cumecs
- H.F.L = 496.075 m
- BED LEVEL = 490.87m
- Mean flood velocity of the stream = 4.5(m/s)
- Mean particle diameter of river material (mm) = 5mm
- Acceleration due to gravity (m/s2) = 9.8 m/s2
- Min Weight of stone Pitching (kg) = 200kg As per IRC.89:2019, Table 5 below)

Table 5: Minimum Weight of Loose and Stones for Pitching on River Slopes

Mean Design velocity (m/s)			**Slope 2:1**	**Slope 3:1**
			Minimum Weight (kg)	**Minimum Weight (kg)**
Up to	2.5		40	40
	3		40	40
	3.5		45	40
	4		100	70
	4.5		200	140

	5		380	260

Notes:

i. No stone weighing less than 40 kg and diameter 300 mm shall, however, be used in case of loose isolated stones.

ii. Where the required size stones are not economically available, cement concrete blocks of equivalent weight or stones in mechanically woven double twisted wire mesh gabions may be used in placed of loose isolated stones.

iii. When stones are confined in mechanically woven double twisted wire mesh gabion or mattress, weight & size of stone should be in accordance with provision of IRC:SP:116.

- Min Weight of stone on horizontal bed (kg) = 113Kg (IS.4262:1995)

The relevant pages of IS code are reproduced below.
Weight of the stone on horizontal bed may be expressed as:

$$\mathbf{W = 0.02323 \frac{S_g}{\left(S_g - 1\right)^3} V^6} \quad (5)$$

Where

W = weight of stone in kg,
S_g = specific gravity of stone, and
V = mean velocity of water in m/s over the vertical under reference.

The weight of stone worked out is the minimum required. Use of higher weight stones will be based on the material available at site, ease of construction, factor of safety, etc.

- Thickness of pitching (mm) = 625.52mm (IRC.89:2019)

Thickness of pitching: Minimum thickness of pitching is required to with stand the negative head created by velocity. This may be determined by the following relationship (IRC: 89-2019) :

$$\mathbf{t = \frac{V^2}{2g(s_g - 1)}} \quad (6)$$

Where,

t = Thickness of pitching in m,
V = Velocity in m/s,
g = Acceleration due to gravity in m/s^2,
S_g = Specific gravity of stones

However, thickness of stone pitching computed from the above formula shall subject to a lower limit of 0.3m in case of loose isolated stones.

Thickness of Apron (mm) ta = 500.417mm (near toe of revetment) (0.8*t)
= 750.625mm (at river end) (1.2*t) IS.4262:1995

Depth of scour below H.F. L(D) = 5.452m …IRC.SP:116:2018
D = 0.473 (Q/f) 1/3

Silt factor (f) may be calculated using the following formula f= 1.76 (d) ½
Max scour depth (Dmax) below H.F.L = 2*D = 10.904m
Max scour depth (Dmax) below Bed level/L.W. L = 5.727m
(Dmax below H.F.L) - (H.F.L-Bed level)

Required Width of launching Apron L = 2*(Dmax) below Bed level (IRC.SP:116:2018)
=11.455m

Length of Launching Apron = greater than 1.5 to 2 times (expected erosion at the most critical section
The typical section of Launching apron is shown in Fig. 1.

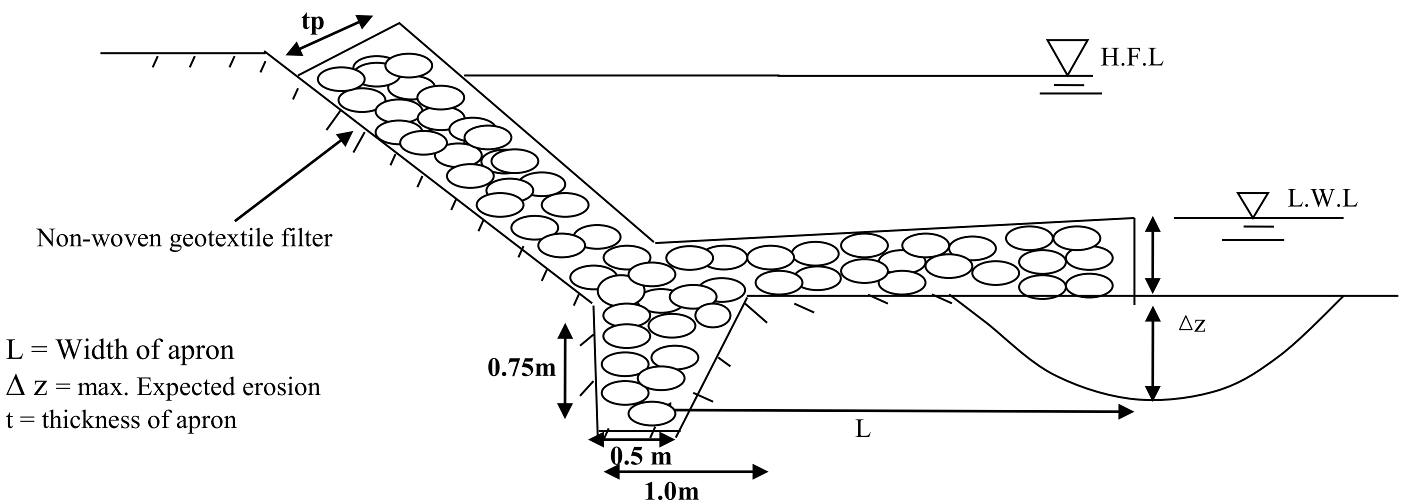

Fig 1: Typical Launching Apron

5. Study of Catchment & Hydrological Parameters of Site

5.1 Study Area

The study area is located near PAONTA SAHIB along the Giri River and watershed of Giri River is located in Himachal Pradesh of India, which is covered by 2531 Sq.km area & situated between 30°30’0” N to 31°17’30” N latitude and 77°3’0” E to 77°40’0” E longitudes. The temperature varies from a minimum of (-) 4 degree Celsius in winter to about 41 degrees Celsius in summer. Annual rainfall of catchment is varying between 1000 and 1200 mm.

The geotechnical parameters of landslide material are as follows (Table 6):

Table 6: Geotechnical Characteristics Of Landslide Sediment

Laboratory analysis	Head sample	Middle sample	Toe sample
Sieve Analysis	SP	SP	SP
Specific gravity	2.68	2.63	2.64
Liquid limit	Non plastic	-	-
Plastic limit	-	-	-
Plasticity Index	-	-	-
Direct shear Test	C=0 $\Phi = 34^{o}$	C=0 $\Phi = 34^{o}$	C=0 $\Phi = 34^{o}$

From the above laboratory analysis couple of points are clear that:

- **i.** The soil deposited is loose and cohesionless with angle of internal friction $\Phi = 34^{o}$. The movement of this slope is basically saturation related where cohesion less landslide debris tries to attain the angle of internal friction.
- **ii.** Self-drilling anchors with chemical grouting and wooden piles can be used to stabilize the upward and downward hill slopes.
- **iii.** For prevention of toe erosion during flood, launching apron can be design to divert the flow of river.

6. Estimation of Design Flood (Peak Only)

Estimation of the peak discharge on the basis of the rainfall has been done as 6028.48 cumecs. Accordingly the protection works has been designed.

7. Design of Concrete Block Size that will not be swept Away

Shear stress in flow, $T_o = \gamma_f DS$, **(i)**

Where γ_f = specific weight of fluid,

D = depth of flow(m), and

S = water slope,

The shear stress due to flow at the bridge abutment which will now be acting as a piers can have instantaneous value upto12 times the normal one.

Taking it to be 4 times the normal value,

$T_o = 4\, \gamma_f DS$

In the present Case,

γ_f= 9810, D = 3.5m & S= 1/30,

Hence, T_o = 4x9810x3.5x1/30 = 4,578 N/m^2

The size of the block that shall not get dislodged by the flood flow is computed as below:

$T_o/\Delta\gamma_s d = 0.22d_0 + 0.06(10)^{-7.7}d_0$, **(ii)**

Where $d_o = [(s-1)gd^3/V^2]^{-0.3}$

In the above relations,

$\Delta\gamma_s = \gamma_s - \gamma_f$, where γ_s = specific weight of block

γ_f= specific weight of water

d = diameter of concrete block

&V = Kinematic Viscosity of water which can be taken = 10^{-6}m^2/s.

If the diameter of C.C. block be 6m,

$d_o\ [(2.4-1)9.81x6^3/10^{-12}]^{-0.3}$

= $2.282x10^{-5}$

From the first relation,

$T_o/(2.4-1)$x 9810x6 = 0.22x2.282x10^{-5}+$0.06(10)^{-7.7\times2.282\times10^{-5}}$= 0.06

Or, T_o = 1.4x9810x6x0.06 = 4944 N/m^2,

Since the resistance T_o of **4944 N/m^2** is more than shear stress due to flow which works out to be **4578 N/m^2**, the C.C. block of 6m^3 diameter will not get dislodged,

Volume of a C.C. block of 6m diameter

$= \pi\, d^3/6 = \pi/6x6^3 = 113.1m^3$ **(iii)**

Hence a C.C. block of $5^m x 5^m x 5^m$ or $7^m x 7^m x 2.5^m$ size will be safe. In order to have further factor of safety, the individual C.C. blocks should be interconnected.

8. Conclusion

The hill slope has been stabilised with the help of anchors (Mittal, 2013). The toe erosion has been controlled with the help of groyens and spurs. The road which was washed away every year, shall now be stopped as a rigid pavement has been provided which is anchored with mircopiles. This highway is very important for H.P. state as it is corridor for fruits crop. Due to shortage of space, fully description of all solutions here was not possible.

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