

7.1. Introduction

In this chapter, the feasibility of the developed Stability Analysis and HAZARD RATING (SAHARA) system for the dump slope structures was verified through case studies. A total of six cases from three different mines were analyzed using the SAHARA system. The results were compared with the conclusions of the scientific reports, existing conditions and outcomes of the survey department of the mines.

The first mine was Mine “X” an opencast coal mine, in Chhattisgarh state of India. Three existing internal dump slopes (A, B, and C) were considered from this mine for the study. The second mine was Mine “Y” an opencast coal mine in Madhya Pradesh, India. A proposed dump slope structure (D) of this mine was examined based on the scientific study. Mine “Z”, an opencast coal mine in Chhattisgarh, India. This mine provided two cases (E and F) in which one had special characteristics due to the mixing of fly ash in the OB dump material (F).

For the assessment of the stability states of the dump slope structure, the proposed SAHARA system requires the measurement of the geometrical and geotechnical. Cases D, E, and F had uniform geometry throughout the dump slope structure. Thus, the representative magnitude of the bench height, bench slope angle, and bench width was easily deduced. However, cases A, B and C were irregular in shape. Therefore, all the benches were reviewed, and prone to failure (i.e., the dimensions of the bench height, bench slope angle, and bench width were situated in a critically stable or unstable state) were identified. It provided the expected value of the bench height, slope angle, and width.

The cross-section profile of each case is represented below. Here, the bottommost bench was counted as the first bench and the topmost bench as the last bench in each dump slope structure. The details of each mine and the case are discussed as follows:

7.2. Case Study of Mine “X”

The Mine “X” has an area of about 19.03 square kilometres in the south-central part of the Korba coalfield in the Korba district of Chhattisgarh, India, as depicted in Figure 7.1. It is included in the Survey of India Topo-sheet No. 64 J/11 and is bounded by latitudes 22°18'00" N to 22°21'42" N and longitudes 82°32'00" E to 82°39'30" E. It is a mega opencast project in the thick seam zone. The coal produced in 2014-15, 2015-16, and 2016-17 were 41 million tonnes (Mte) per annum. The OB extracted in 2014-15 was 45.44 million cubic meters (Mm^3), in 2015-16 was 44.01 Mm^3 and in 2016-17 was 47.07 Mm^3 . The general topography of the mining area is gently undulating and varies 288-328 m above mean sea level. The coal block exhibits a rolling strike throughout the area. The strata, including the coal seams, show a broad E-W trend. The strata, in general, show a southerly dip. The general dip of the strata varies from 2°-4° in the Central & North-Eastern part. The strata dip goes from 6°-8° in the South-East and Western parts (IIT-BHU 2021).



Fig. 7.1 Mine “X”, opencast coal mine (SECL), Chhattisgarh, India.

7.2.1. Internal Dump A

The profile coordinates of the internal Dump A were obtained from the survey department of the mine and are represented in Figure 7.2. Dump A had three benches. The height of the first, second, and third benches were 34, 46, and 40 m, respectively. There was an elevation of 2 m along the bench width between the second and third benches. Hence, the total dump height was 122 m. The bench slope angle of the first bench was 28° , the second bench was 51° , and the last bench inclined 22° with the horizontal plane. The bench width was absent between the first and second bench, and a bench width of 97 m was provided between the second and third bench. The OB dump material possessed cohesion of 21 kPa, friction angle of 28° , and density of 1760 kg/m^3 (IIT-BHU 2021). In the second bench, the bench slope angle was in an unstable state, and bench width was also not provided between the first and second bench. The second bench was more susceptible to failure, but the heights of all three benches were located in the critically stable state range. Therefore, the overall stability of the dump slope structure was analyzed based on the three different cases. The bench height, slope angle, and width were changed in each case as per the bench configuration, and the remaining parameters were the same.

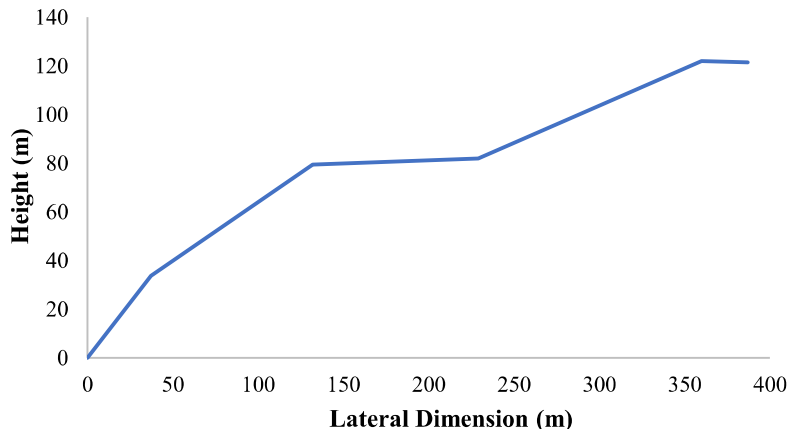


Fig. 7.2 Internal Dump A, Mine “X”, India (IIT-BHU 2021)

Table 7.1 summarizes the determined rating and PoF using Table 6.8 with due consideration of all seven stability governing parameters of cases 1, 2, and 3. In all three cases, the geotechnical properties were found near the boundary value of a stable and critically stable state. In geometrical parameters, all cases had bench height in the critically stable state range, but the bench slope angle and width were in the unstable state in case 2. The summation of rating was in a stable state for cases 1 and 3 with PoF in a critically stable state. The summation of the rating and PoF of case 2 were 45.45 and 100%, respectively.

Table 7.1 Dump A slope stability state analysis based on rating and PoF

Parameters	Case 1	Case 2	Case 3
Total Dump Height (m)	122	122	122
Bench Height (m)	34	46	40
Bench Slope Angle (°)	28	51	22
Bench Width (m)	100	nil	97
Cohesion (kPa)	21	21	21
Friction Angle (°)	28	28	28
Density (kg/m ³)	1760	1760	1760
Rating	83.17	45.45	89.74
PoF	0.35%	100%	1.03%

The overall actual and predicted condition of internal Dump A is described in Table 7.2. The internal Dump A had FoS of 0.76, XDIS of 35000 mm, and SSI of 50 as per the scientific report (IIT-BHU 2021). The stability state range classified in Table 5.3 also predicted the same stability state as found in the scientific report. The summation of the rating would be less than 64.1 and PoF would be greater than 41.3% in unstable state conditions as per Table 6.9. The lowest value of rating and greatest value of PoF were considered among the three cases to assess the worst scenario. Thus, the rating was 45.45

with a PoF of 100%, and the overall stability state of internal Dump A was unstable. Hence, the predicted stability condition matched well with the actual condition.

Table 7.2 Actual and predicted conditions using the SAHARA system of Dump A

Stability Analysis Parameters	Actual (IIT-BHU 2021)	Predicted
FoS	0.76	Unstable
XDIS (mm)	350000	Unstable
SSI	50	Unstable
Rating	--	Unstable
PoF (%)	--	Unstable
Overall Stability Condition	Unstable	Unstable

7.2.2. Internal Dump B

The configuration of the internal Dump B with a total dump height of 105 m is displayed in Figure 7.3. The dump structure had two benches with critical parameters, and the parameter of one bench belonged to an unstable state. Therefore, three cases were designed to analyze the stability of the dump slope structure. Case 1 carried a bench height of 37 m, bench slope angle of 38.83° , and bench width of 100 m. In case 2, the bench height was 65 m with a bench slope angle of 26.58° and a bench width of 52 m. The bench height (45 m) was in the critically stable state, and the bench slope angle (35.56°) and bench width (112 m) were placed in a stable state condition in the last case. The geotechnical properties were the same as adopted in internal Dump A.

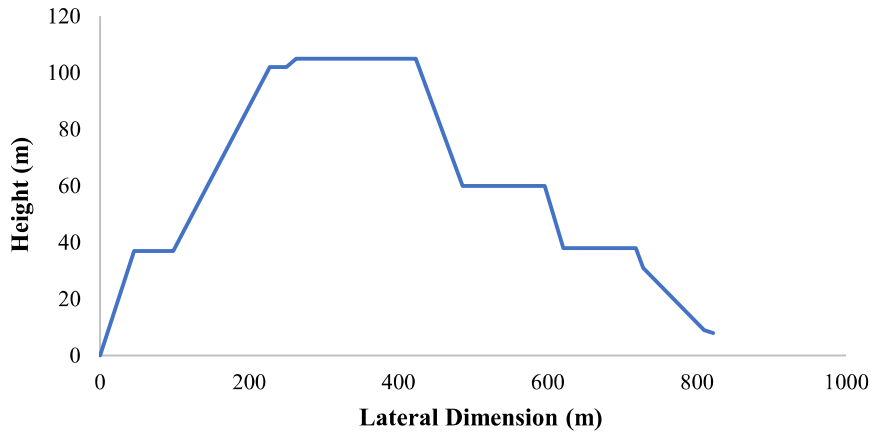


Fig. 7.3 Internal Dump B, Mine “X”, India (IIT-BHU 2021)

The rating and PoF of Dump B were calculated based on the stability rating and hazard quantification chart. The rating of cases 1, 2, and 3 were 75.82, 76.52, and 77.23, respectively (Table 7.3). A slight difference existed in the rating of each case. The rating of each case followed the range of stable state but was present close to the transition state of stable to critically stable. However, a notable contrast was observed in the PoF of each case. Case 1 and 3 had PoF of 0.93% and 3.59%, but it increased rapidly to 35.92% in case 2. The magnitude of PoF of each case followed the range of critically stable state conditions.

Table 7.3 Dump B slope stability state analysis based on rating and PoF

Parameters	Case 1	Case 2	Case 3
Total Dump Height (m)	105	105	105
Bench Height (m)	37	65	45
Bench Slope Angle (°)	38.83	26.58	35.56
Bench Width (m)	100	52	110
Cohesion (kPa)	21	21	21
Friction Angle (°)	28	28	28
Density (kg/m ³)	1760	1760	1760
Rating	75.82	76.52	77.23
PoF	0.93%	35.92%	3.59%

The actual condition and performance measuring parameters of Dump B were extracted from the scientific report (IIT-BHU 2021) (Table 7.4). The safety factor was close to 1 with a maximum horizontal displacement of 4 mm and shear strain increment of 0.0007. The safety factor and PoF adhered to the critically stable state condition based on the prediction, but the horizontal displacement and shear strain increment complied with the stable state condition. Since dump slope system components were considered in the series system, shifting the stability state of one parameter to a critically stable or unstable state may lead to instability. Similarly, it was perceived that alteration of one performance measuring parameter towards the instability state might cause the failure of the dump slope structure. Thus, the stability state of the dump slope was forecasted as critically stable and it coincided with the observed actual stability condition.

Table 7.4 Actual and predicted condition using the SAHARA system of Dump B

Stability Analysis Parameters	Actual (IIT-BHU 2021)	Predicted
FoS	1.10	Critically Stable
XDIS (mm)	4	Stable
SSI	0.0007	Stable
Rating	--	Stable
PoF (%)	--	Critically Stable
Overall Stability Condition	Critically Stable	Critically Stable

7.2.3. Internal Dump C

The total dump height of the Dump C slope structure was 183 m. Figure 7.4 illustrates the cross-section based shape of the Dump C slope. The dimensions of the benches were not consistent from the bottom to the top of the dump slope. The dump had one high bench on the right side of 60 m with a bench slope angle of 35.24°. During the analysis of the Dump C profile, it was noticed that the dump consisted of four major critically stable cases including the right side 60 m bench. The geometrical and geotechnical details

of all four cases are discussed in Table 7.5. Case 1 had the highest rating and lowest PoF among all cases. Cases 2, 3, and 4 produced ratings close to each other, but there was a huge difference in the PoF. Case 3 depicted the highest PoF of 79.74%, followed by Case 4 with a PoF of 41.92%, and the PoF of Case 2 was 8.78%. The rating of case 1 placed it in a stable state condition while the remaining cases were situated in a critically stable state condition. The PoF of cases 1, 2, and 4 came under a critically stable state while case 3 was in an unstable state.

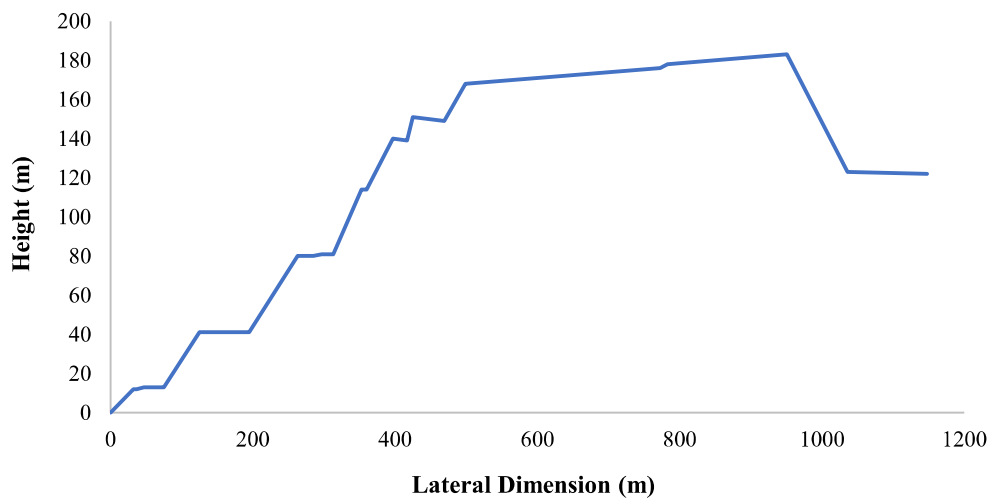


Fig. 7.4 Internal Dump C, Mine “X”, India (IIT-BHU 2021)

Table 7.5 Dump C slope stability state analysis based on rating and PoF

Parameters	Case 1	Case 2	Case 3	Case 4
Total Dump Height (m)	183	183	183	183
Bench Height (m)	39	33	26	60
Bench Slope Angle (°)	29.85	39.54	35.11	35.24
Bench Width (m)	70	16	7	112
Cohesion (kPa)	21	21	21	21
Friction Angle (°)	28	28	28	28
Density (kg/m ³)	1760	1760	1760	1760
Rating	80.75	72.09	73.84	70.26
PoF (%)	1.07	8.78	79.74	41.92

The current circumstances of Dump C are reported in Table 7.6 and compared with the predicted results. The Dump C was on the verge of instability as it possessed a FoS of 1.06. The XDIS was 20 mm with an SSI of 0.0025. The XDIS moved a little bit ahead of the stable state limit while SSI was at the boundary line of stable and critically stable state condition. The proposed criteria of FoS, XDIS, SSI, and rating classified the stability status of Dump C as critically stable. However, the instability could occur if presumed spatial variability exists as PoF was spotted in an unstable state.

Table 7.6 Actual and predicted conditions using the SAHARA system of Dump C

Stability Analysis Parameters	Actual (IIT-BHU 2021)	Predicted
FoS	1.06	Critically Stable
XDIS (mm)	20	Critically Stable
SSI	0.0025	Critically Stable
Rating	--	Critically Stable
PoF (%)	--	Unstable
Overall Stability Condition	Critically Stable	Critically Stable

7.3. Case Study of Mine “Y”

Mine “Y” is situated in the south-central part of the Moher sub-basin of Singrauli coalfields in the Singrauli district of Madhya Pradesh in India (Figure 7.5). The Singrauli coalfields cover a total area of 2202 sq. km. The Singrauli main basin spread over 1890 sq. km. The Moher Sub-basin covers the remaining 312 sq. km. area. A large portion of the Moher Sub-basin lies in the Singrauli district of Madhya Pradesh and a small part is situated in the Sonebhadra district of Uttar Pradesh. There are 10 highly mechanized operating opencast mines in the Moher Sub-basin (Northern Coalfields Limited, 2021). Mine “Y” is bounded by latitudes 24°06’3.29” & 24°11’16.37” North and longitudes 82°35’28.23” & 82°39’50.12” East. It has a hilly plateau with a varying elevation between 400-450 m above mean sea level, and some area has an elevation greater than 500 m. The

mine has total geological and mineable coal reserves of 504.61 and 483.01 MTe, respectively with an overburden of 1776.65 Mm³ and an average stripping ratio of 3.68 m³/te. The coal seam has a flat gradient of 2° - 3° (CMPDI 2019).



Fig. 7.5 Mine “Y”, opencast coal mine of Singrauli coalfields (NCL), India

7.3.1. External Dump D

IIT-BHU (2017) proposed the design approach for external dump D, Mine “Y”. The total dump height was 150 m, comprising 5 benches, and all benches were symmetrical (Figure 7.6). Each bench had a height of 30 m with a bench slope angle of 30°. Each bench was separated from the other by providing a bench width of 20 m. The overall slope angle was maintained at 23.8°.

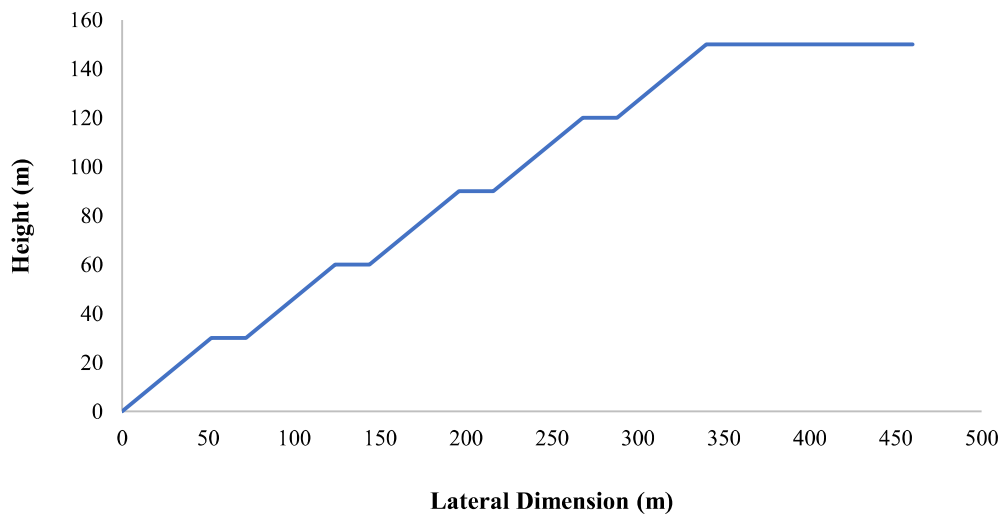


Fig. 7.6 Profile of proposed external Dump D (IIT-BHU 2017)

The bench width and geotechnical parameters followed the critically stable state range, as expressed in Table 7.7. However, the friction angle and density were close to the stable state. The cohesion and bench width were situated approximately in the middle of a critically stable state. According to Table 6.6, the bench slope angle has the strongest influence on the dump slope structure, followed by friction angle and bench height. The cohesion and density affect the dump slope stability but are not as intense as the bench slope angle, friction angle and bench height. Moreover, the bench width is also placed in the middle of the ranking among the parameters.

The rating of the D dump slope was situated in the stable state condition due to maintaining the highest influencing parameters in the stable state to mitigate the effect of the critically stable state parameters. Thus, maintaining the bench slope angle, bench height, and total dump height in a stable state condition kept the summation of rating in the stable state category. The PoF crossed the stable state range slightly due to the presence of four parameters in a critically stable state and adopted a range of uncertainty.

Table 7.7 Dump slope stability state analysis of Mine “Y” based on rating and PoF

Parameters	D
Total Dump Height (m)	150
Bench Height (m)	30
Bench Slope Angle (°)	30
Bench Width (m)	20
Cohesion (kPa)	18
Friction Angle (°)	28
Density (kg/m ³)	1890
Rating	78.44
PoF (%)	2

The proposed dump D was stable as FoS was 1.37, XDIS was 4 mm, and SSI was 0.0015 (IIT-BHU 2017). All the predicted performance measuring parameters agreed with the stable state condition except PoF (Table 7.8). The PoF moved ahead slightly from the stable state range and was placed in a critically stable state due to consideration of the high range of spatial variability of geotechnical parameters. However, the magnitude of PoF will be reduced if a low range of uncertainty exists in the dump D.

Table 7.8 Actual and predicted conditions using the SAHARA system of dump D

Stability Analysis Parameters	Actual (IIT-BHU 2017)	Predicted
FoS	1.37	Stable
XDIS (mm)	4	Stable
SSI	0.0015	Stable
Rating	--	Stable
PoF (%)	--	Critically Stable
Overall Stability Condition	Stable	Stable

7.4. Case Study of Mine “Z”

Mine “Z” has an area of about 1018.925 hectares and is located in the southeastern part of the Korba coalfield in the Korba district of Chhattisgarh, India, as depicted in Figure 7.7. It started in the year 1966 with a total mineable reserve of 101.50 Mt. It is included in the Survey of India Topo-sheet No. 64 J/11 (1:50000) and is bounded by latitudes 22°19'00" N to 22°19'30" N and longitudes 82°42'30" E to 82°44'30" E. The area has levelled plain terrain and a local steep approach towards the streams and nallahs in the northeastern plain. The average elevation of the mine block varies between 274 to 293 m. The mine has a general elevation towards the West direction, but the highest elevation is towards the block of Nort-East and lowest towards the South-West area. In 1966, the mine was planned to produce 1.0 Mte Per Annum (MTPA). The production was set to 2 MTPA

in 1976 based on the report of CMPDIL. The production was 4.90 MTPA in 2020 and expanded to 5.25 MTPA in 2022 (CMPDI 2018, Ministry of Coal 2022).



Fig. 7.7 Mine “Z” opencast coal mine (SECL), Korba, Chhattisgarh, India

IIT-BHU (2019b) formulated the design of two dump slope structures, one for the pure dump material (E) and the other for the fly ash mixed dump slope (F). The total dump height of both the dump slope was 120 m as represented in Figure 7.8. The cohesion, friction angle, and density of Dump E were higher than Dump F (Table 7.9). Therefore, the bench slope angle of Dump E was steeper than Dump F. The bench height was equal to the bench width, i.e., 30 m in both the dump slope structure. The bench slope angle was 40° in pure dump slope and 35° in fly ash mixed dump slope. The difference between the rating and PoF of both dump slopes was minimal. The rating of both dump slopes followed the stable state range. However, the PoF of dump E and F was situated in a critically stable state but very close to the boundary point of a stable and critically stable state.

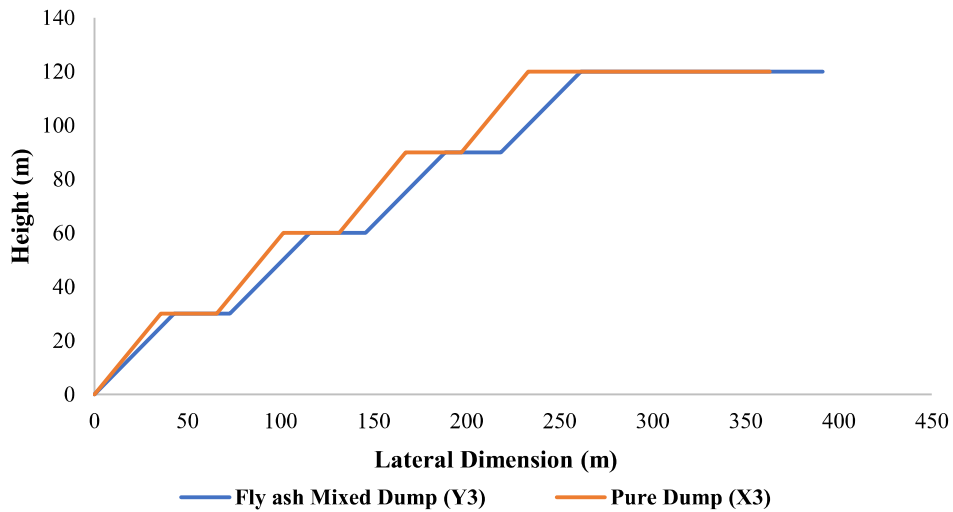


Fig. 7.8 Dump slope structure profile of Mine “Z” opencast coal mine (IIT-BHU 2019b)

Table 7.9 Dump slope stability state analysis of Mine “Z” based on rating and PoF

Parameters	E	F
Total Dump Height (m)	120	120
Bench Height (m)	30	30
Bench Slope Angle (°)	40	35
Bench Width (m)	30	30
Cohesion (kPa)	19	15
Friction Angle (°)	36	32
Density (kg/m ³)	1920	1780
Rating	78.67	78.43
PoF (%)	0.64	0.50

The actual condition of the proposed design of Dump E and F was stable (IIT-BHU 2019b). The comparison of the actual and predicted condition of pure and fly ash mixed dump was summarized in Table 7.10. The safety factor, horizontal displacement, and shear strain increment of the Dump E coincided with stability state criteria. The safety factor and shear strain of dump F are also in a stable state condition. However, horizontal

displacement slightly exceeded the stable state and entered a critically stable state condition. The scientific report mentioned that the horizontal displacement exceeded the stable design limit at the skin of the slope surface, but the expected zone of instability was negligible. The rating of both dumps was placed in the stable state category, and the PoF was located in a critically stable state. The difference between predicted PoF was small and close to the boundary of stable state condition. The forecasted PoF would only occur when such a spatial variation of geotechnical properties exists in designed dump slope structures. Thus, the overall predicted condition of both the dumps was stable, and it followed the outcomes of the scientific report.

Table 7.10 Actual and predicted conditions using the SAHARA system of Mine “Z” dump

Stability Analysis Parameters	E		F	
	Actual (IIT-BHU 2019b)	Predicted	Actual (IIT-BHU 2019b)	Predicted
FoS	1.30	Stable	1.33	Stable
XDIS (mm)	2	Stable	15	Critically Stable
SSI	0.0007	Stable	0.002	Stable
Rating	--	Stable	--	Stable
PoF (%)	--	Critically Stable	--	Critically Stable
Overall Stability Condition	Stable	Stable	Stable	Stable

7.5. Summary

Here, the validation of the proposed SAHARA system was done by comparing its forecasted outcomes with the findings of the scientific reports. The performance of the designed system was scrutinized using five performance measuring parameters and their range corresponding to the different stability state conditions. The performance

measuring parameters were the safety factor, maximum horizontal displacement, maximum shear strain increment, summation of ratings and probability of failure. It was observed that the formulated SAHARA system precisely evaluated the stability of the uniform and nonuniform dump slope structure. Moreover, it could pinpoint the most vulnerable bench in a large-size multi-bench dump slope structure. The prominent points of the SAHARA system based on the case studies are discussed below:

- The rating of the multi-bench dump slope structure was determined by considering the bench that was present in a critically stable or unstable state. When more than one vulnerable bench existed the final stability rating of the dump slope structure was decided based on the lowest summation of the rating.
- The chances of instability of a critically stable dump slope can be reduced by adjusting the controllable input parameters into the stable state range.
- The PoF is more sensitive than the summation of the rating as it is based on a complex multiplication function. The sensitivity of the PoF could be reduced by increasing the confidence in the uncertainty of geotechnical properties. Thus, the PoF was utilised as a supplementary performance measuring parameter to depict the maximum chances of instability.
- It was observed that the FoS, XDIS, SSI, and stability rating must be situated in the stable state range for designing a stable dump slope structure.