MAXIMUM SAFE SLOPE ANGLES FOR PROPOSED SHIPLOCKS OF THE THREE GORGES DAM SITE BASED ON KINEMATIC ANALYSES PERFORMED ON MAJOR DISCONTINUITIES

by

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Abstract. The Three Gorges Project has been proposed to harness the great hydrologic power potential of the Yangtze River, which is the largest river in China. The depth of rock excavation needed to construct the permanent navigation structures (shiplocks) is high, with a maximum of 170m in some locations. The granitic rock mass which exists in the shiplock region contains a number of major discontinuities and about four sets of minor discontinuities. One hundred and thirty three major discontinuities have been mapped around the shiplock covering an area of 1740×600m. Kinematic analyses were conducted using the major discontinuities to estimate maximum safe cut slope angles with respect to plane sliding, wedge sliding and toppling failure. Kinematic analysis for plane sliding has resulted in maximum safe cut slope angles greater than 65° for most of the discontinuities. For most of the wedges, maximum safe cut slope angles greater than 45° were obtained. Maximum safe slope angles greater than 85° were obtained for most of the discontinuities in the toppling case. It seems that the shiplock faces in the proposed permanent shiplock region in fresh rock are stable up to a cut slope of about 45°. However, it is important to keep in mind that this conclusion is based on the kinematic analyses performed using only the major discontinuities. Further kinematic as well as kinetic analyses are recommended incorporating minor discontinuities, water forces, earthquake forces, etc., before making the final conclusions about maximum safe cut slope angles for the shiplock region.

Additional Key Words: Rock, Slope Stability.

Introduction

The Yangtze River is the largest river in China. From its headwaters to its estuary, the Yangtze River meanders over 6,300 km (Fig. 1) and its annual runoff into the sea amounts nearly 1,000 billion m^3 (Ha 1993). Its total drop is more than 5,800 m with a water power potential of up to 268,000 Mw. In order to harness the river and develop its water resources, extensive efforts in investigation, planning, design and scientific research have been conducted for nearly forty years. The Three Gorges Project has been proposed in order to exploit the great hydroelectric power potential of the Yangtze River. The project has tremendous multi-purpose benefits such as flood control, electric power generation, navigation, irrigation, tourism and fishery enhancement.

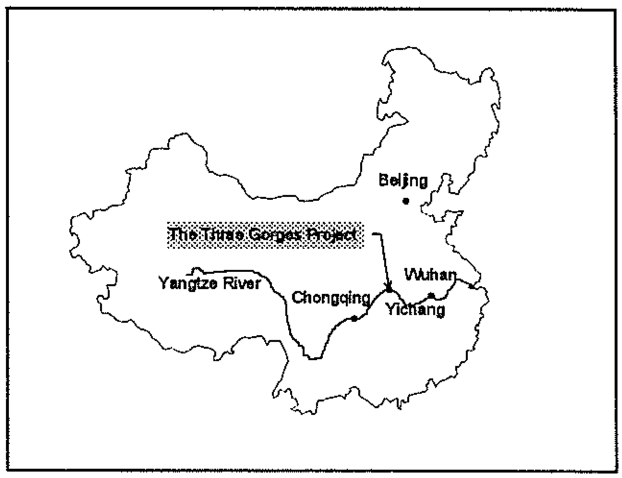

Figure 1. Geographical positions of Yangtze River and Three Gorges project in China.

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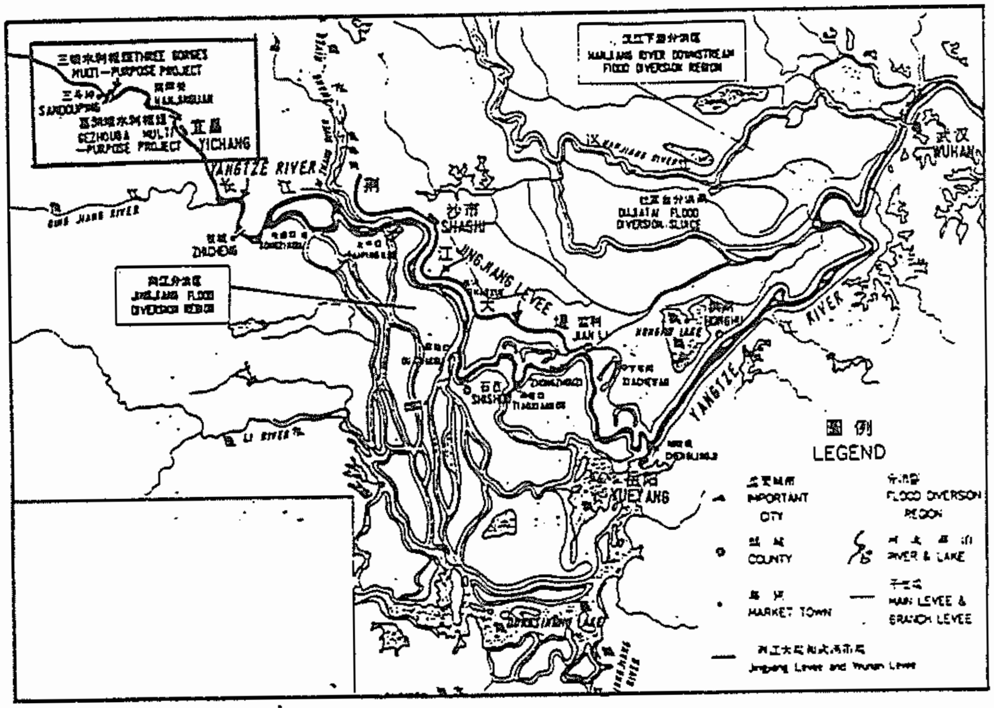


Figure 2. Locations of the planed Three Gorges Project and the completed Gezhouba project on the Yangtze River, China.

The river stretches from Fengjie to Yichang, about 200 km, and cuts through three majestic canyons, Qutang Gorge, Wuxia Gorge and Xiling Gorge - known as the Three Gorges. The Three Gorges Project is located in the middle of Xiling Gorge, about 40 km upstream of the Gezhouba water conservancy project which was completed in 1988, with its dam site at Sandouping in Yichang, Hubei Province (Fig. 2). The construction of Gezhouba dam was done not only with the aim of gaining the immediate benefits from electricity generation and navigation improvement, but also as a rehearsal for the construction of the proposed Three Gorges Project. The China Three Gorges Project Development Corporation, established in 1984, is in charge of the construction of the gigantic project. The Yangtze (Changjiang) Water Resource Commission (formally Yangtze Valley Planning Office) is in charge of the investigation, planning and design of the project (Chen 1986).

The project is composed of concrete dams, flood discharging facilities, power houses, sluice outlets, and navigation structures (Fig. 3). The concrete gravity dam will have a crest length of 2000m and a maximum height of 175m. The expected total reservoir storage capacity is 30.93 billion m^3. The normal water depth of the three Gorges reservoir is expected to be around 175m. The total generating capacity of the power stations will be about 18,200 Mw. The permanent navigation facilities will be located on the left bank, consisting of a five-stage double-lane shiplock (Fig. 4) with effective dimensions of 280 x 34 x 5 m (length x width x water depth) and a one-way shiplift with effective dimensions of 120 x 18 x 3.5 m. During the construction period, a temporary one-way shiplock is scheduled to be built (Fig. 3). The project construction began in October 1993. The total estimated construction time for the project is 18 years. For further details related to the project construction, the reader is referred to the report by Ha (1993). The dip direction (with respect to North) of the downstream axis of the permanent shiplock is 111 degrees. The depth of rock excavation needed to construct the permanent shiplocks is high with a maximum of 170 m in some locations. Operational

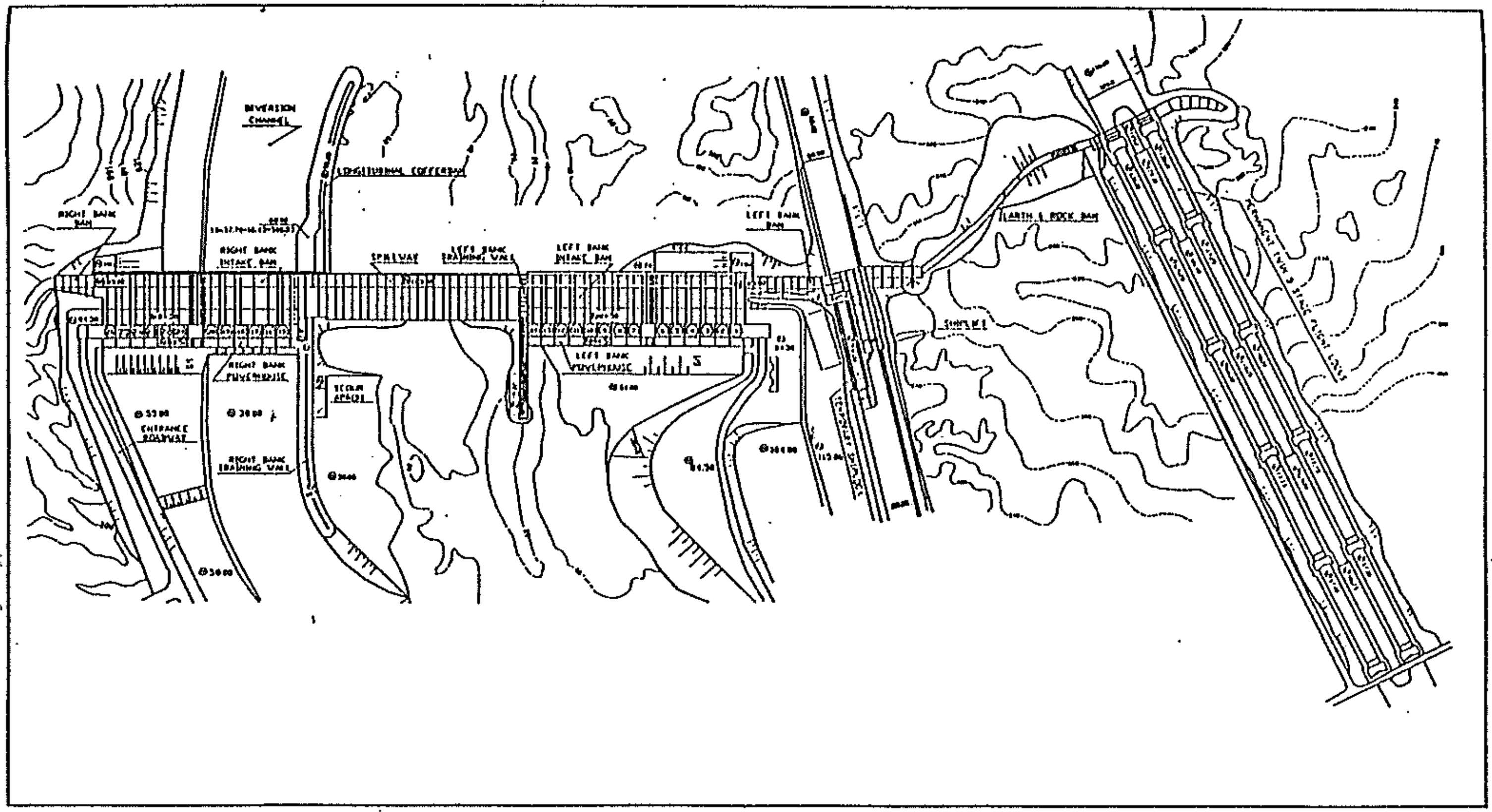


Figure 3. Layout of the Three Gorges Project [after Ha(1993)].

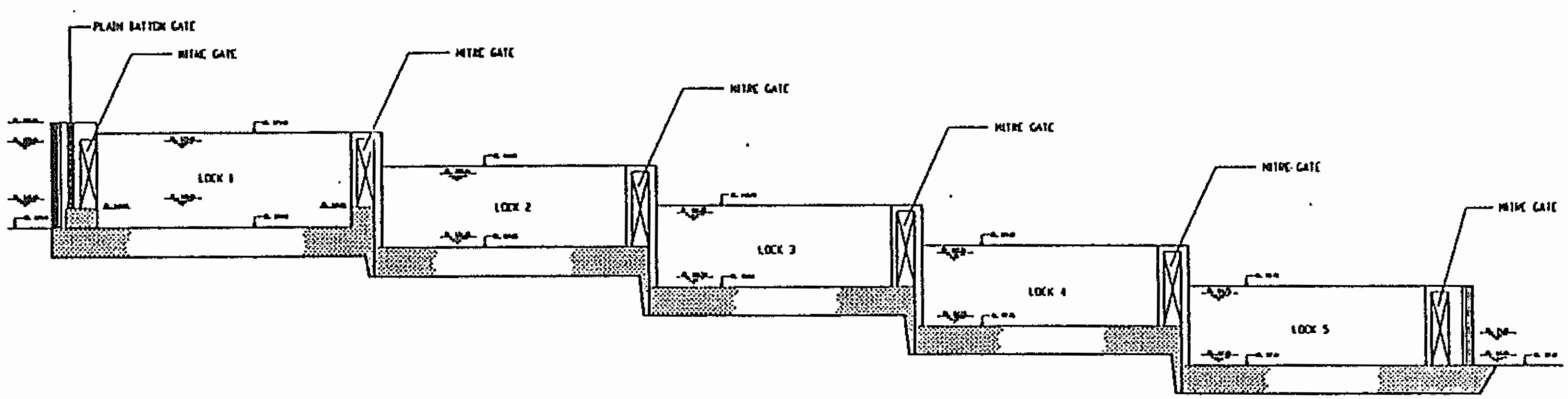


Figure 4. A vertical sectional view of the permanent shiplocks [after Ha(1993)].

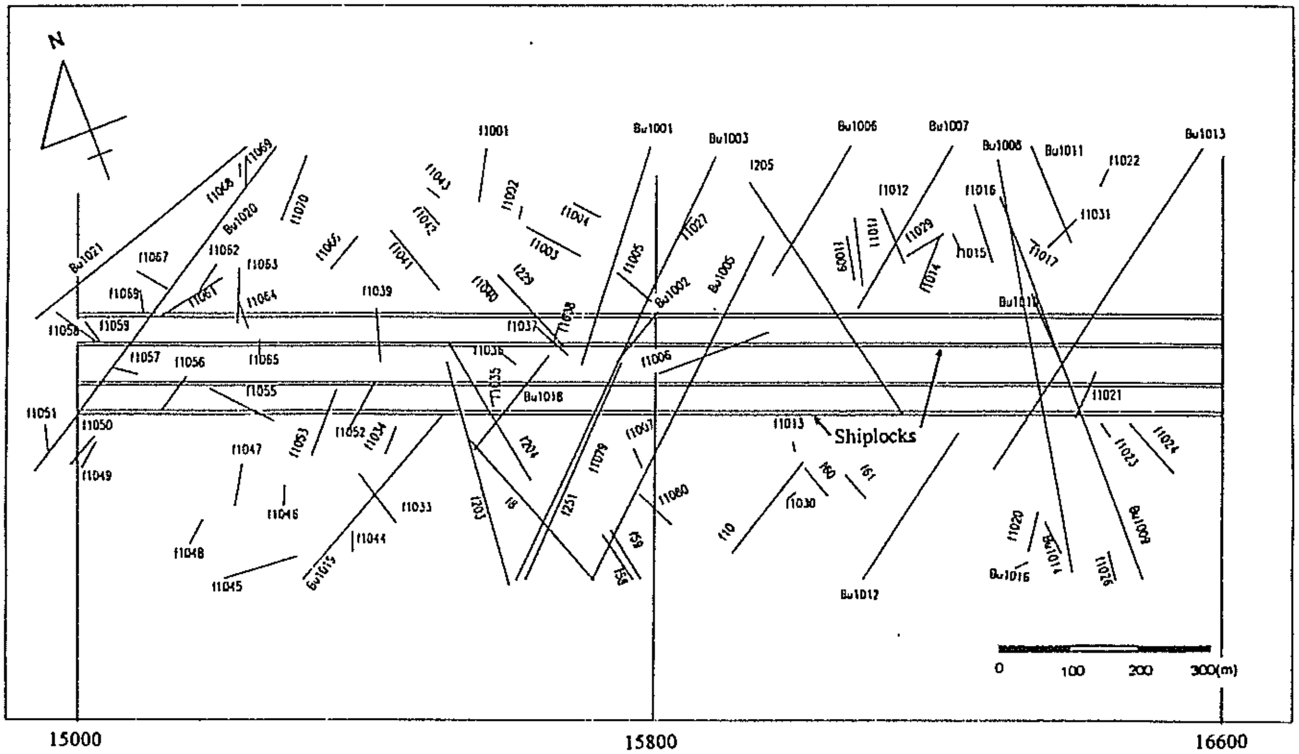


Figure 5. Major discontinuities in the proposed permanent shiplock area.

conditions of the shiplocks demand steep rock slopes on either side of the shiplocks which are about 1600 m long (Fig. 5). The granitic rock mass which exists in the shiplock region contains a number of major discontinuities, and a number of sets of minor discontinuities. Therefore, The rock engineering problems of high, steep rock slopes in the shiplock region are very complicated. Rock mass failures in the shiplock region must be fully prevented to assure safe travel of people in the ships and flood-free conditions downstream. Therefore, it is important to devise a design scheme to provide stable, steep, high rock slopes in the shiplock region. To achieve this ultimate goal, the first step was to characterize the discontinuity network in the rock mass close to the proposed permanent shiplock region (Kulatilake et al. 1996). This was done using about 2050 discontinuity trace data as mapped on the walls and the roof of a 400 m tunnel which is located close to the proposed shiplock region. This paper describes the second step performed towards reaching the ultimate goal. Note that further research is necessary to reach the ultimate goal.

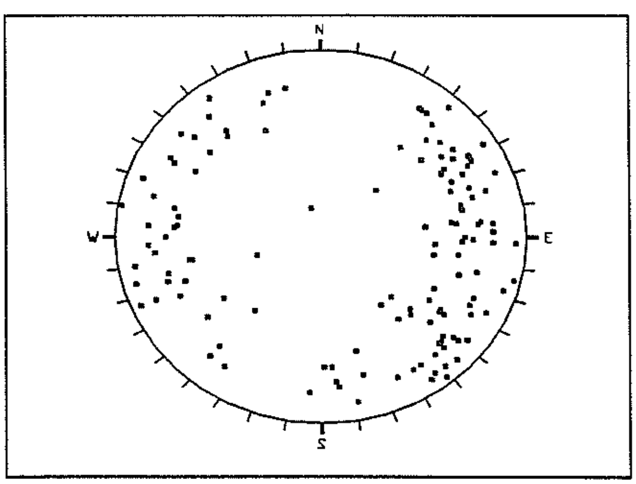


Figure 6. Orientation distribution of major discontinuity poles in the shiplock area on a lower hemisphere equal-area polar diagram.

Geology

Comprehensive geological research for the Three Gorges Region has been in progress since 1950s and is still continuing. The dam site of the Three Gorges Project is situated in the south part of the Huanglin anticline. The Huanglin anticline is 72 km long along the north-south (NS) direction and 35 km wide. It consists of crystalline rock masses of a presinian system. The major rock type is Huanglin granite (hornblend-biotite-plagioclase granite) which is about 90% of the total area of the dam site, with the other being diorite. There are many intrusive dikes in the rock mass. The fresh granite and diorite are hard, with saturated compressive strengths around 100 MPa and 140 MPa, respectively. The ground surface has been seriously weathered. The thicknesses of weathered layers are different in ridges and ravines with an average thickness of 20-40 m. According to the degree of weathering, the rock mass is classified into 4 types (Wang 1986): (a) completely weathered, (b) strongly weathered, (c) weakly weathered, and (d) slightly weathered and fresh rock. The major rock type in the shiplock area is granite with the other being diorite. Diabase, quartzose and pegmatite can be found in the dikes or reefs. Also, lenses of Horneblende Schist can be found.

Major Discontinuities (Faults and Dikes) in the Proposed Shiplock Region

One hundred and thirty three major discontinuities have been mapped around the permanent shiplock covering an area of 1740x600m. Figure 5 shows the locations as well as the strike directions for these major discontinuities. Figure 6 shows the pole distribution of these major discontinuities on a lower hemispherical equal-area polar diagram. High orientation variability of the major discontinuities is well depicted by the polar diagram. Predominant strike directions of the major discontinuities seem to be along NEE-SWW and NW-SE directions. Most of them have steep dip angles varying between 60-70°. The lengths of most of these major discontinuities are expected to be between 50 and 100m. The friction angle (ϕ_j) values of the major discontinuities range from 35° to 45°. To obtain conservative results, the minimum value of ϕ_j of 35° was used in the performed kinematic analyses.

Kinematic Analyses

"Kinematic" refers to the motion of bodies without reference to the forces that cause them to move (Goodman 1989). Kinematic analyses are very useful to investigate possible failure of rock masses which contain discontinuities. Failure involving movement of rock blocks on discontinuities combine one or more of the three basic modes-plane sliding, wedge sliding and toppling. For the proposed permanent shiplock region, kinematic analyses were performed to estimate maximum safe slope angles with respect to the aforementioned three basic failure modes. The basic concepts related to estimation of maximum safe slope angles for the three basic modes of failure are briefly explained below.

Plane Sliding

Consider the case of plane sliding under gravity alone as shown in Fig. 7(a). Any block tending to slide on a single plane surface will translate down the slope parallel to the dip of the discontinuity. If a cut slope is inclined at an angle α to the horizontal, the conditions for a plane slide are that the dip vector of the discontinuity, D, be pointed into the free space of the excavation and plunge at an angle less than α. If δ is greater than α, the block will be stable and no sliding will take place.

This concept can be represented on the stereographic projection (Fig. 7(b)). The cut slope can be constructed as a great circle in the lower hemisphere. D_1 is the dip vector of discontinuity plane 1, and D_2 is the dip vector of discontinuity plane 2. δ_1 and δ_2 are dip angles of planes 1 and 2, respectively. In this example, δ_1 is less than α, and therefore, plane 1 would allow a plane slide. On the other hand, δ_2 is greater than α and plane 2 would not allow a plane slide. In other words, if the dip vector of the discontinuity plane lies in the shaded region, then the plane would allow a slide. The limiting situation arises when the great circle of the cut slope passes through the dip vector of the discontinuity plane. When this occurs, the dip angle of the cut slope corresponds to the maximum safe slope angle with respect to plane sliding.

Figure 7(c) shows the reverse situation. If the dip vector of a discontinuity surface is known, it is possible to determine the maximum safe slope angle corresponding to a cut of assigned strike. The maximum safe slope angle α is the dip of the great circle passing through the given strike and the known dip vector D.

It is important to note that in the case of plane sliding under self weight alone, failure can occur only if the surface of sliding dips steeper than ϕ_j. Therefore, in a lower hemispherical stereographic projection, if a dip vector D of a discontinuity lies in the shaded area in Fig. 7(d), plane sliding will not occur under any cut slope angle. That means the corresponding maximum safe cut slope angle is 90°. Thus, it is necessary to use the concepts shown in both Figs. 7(c) and (d) in estimating the maximum safe cut slope angles under the plane sliding situation.

Wedge Sliding

Sliding along a line of intersection occurs when two discontinuity planes intersect to make a wedge. Figure 8 shows how to obtain graphically the

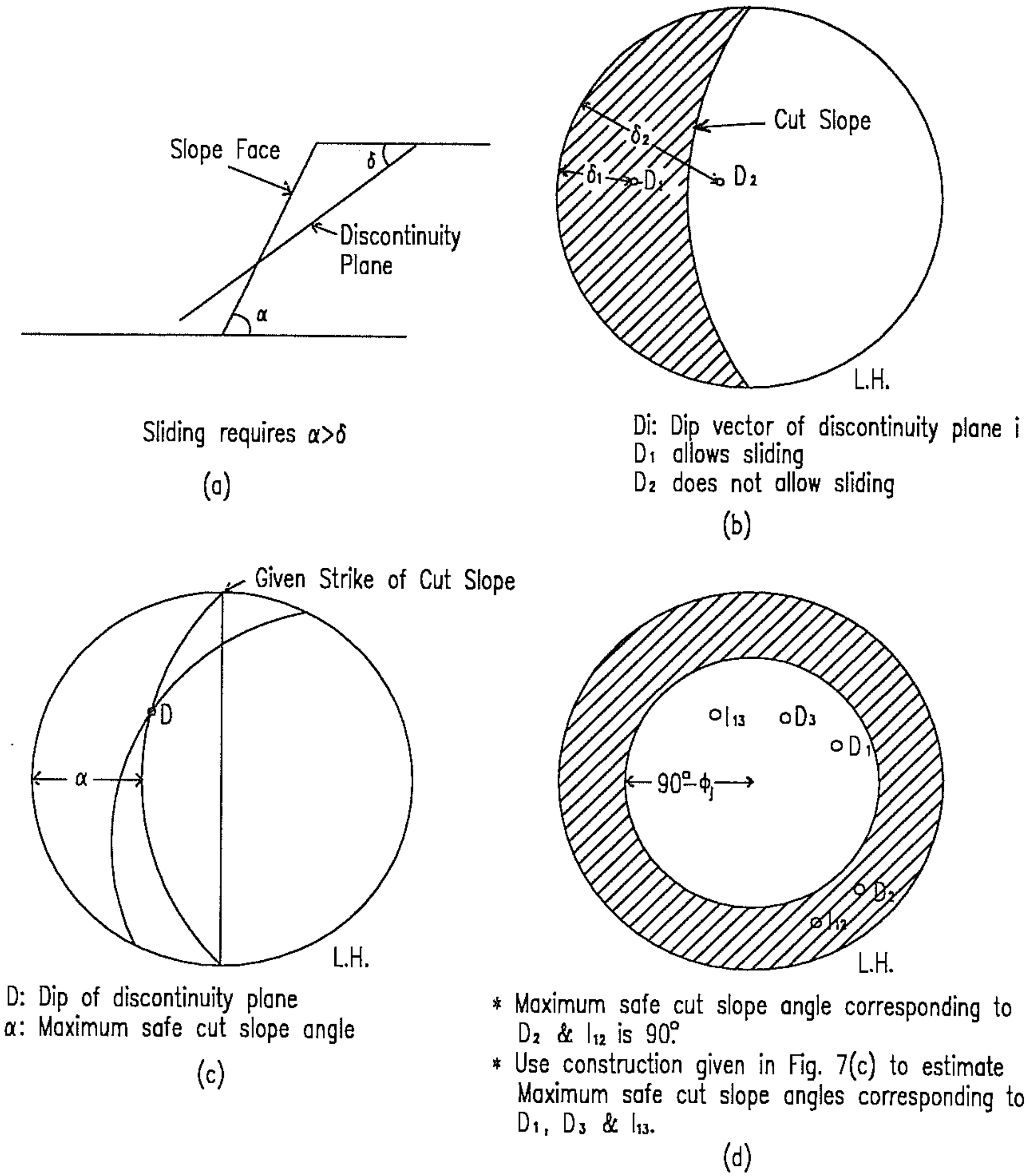
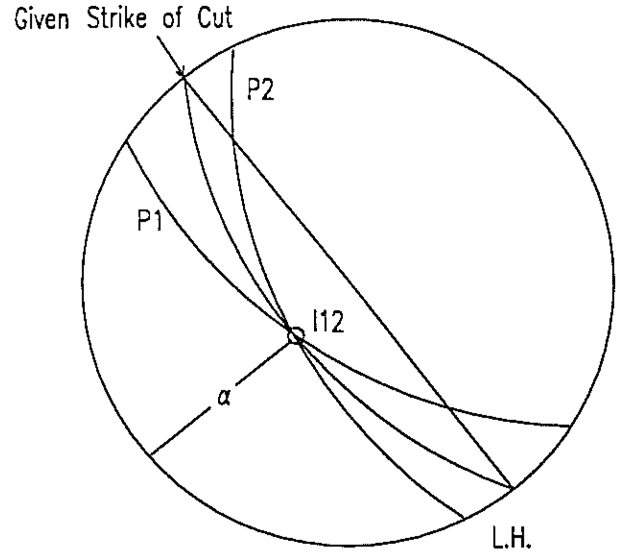


Figure 7. Concepts related to kinematic analysis for plane sliding [Goodman(1989)] (a) daylighting requirements on a pictorial diagram. (b) daylighting requirements on a stereographic plot. (c) great circle for cut slope providing the maximum safe slope angle. (d) influence of ϕ_j on maximum safe cut slope angle.

maximum safe cut slope angle for a possible sliding wedge. When discontinuity planes 1 (P1) and 2 (P2) make a wedge, the maximum safe slope angle for a cut slope of assigned strike can be found in a similar way to the plane sliding case. If the cut is made with the strike as shown in the figure, the maximum safe slope angle α is obtained by the dip of the great circle which passes through the intersection of planes 1 and 2 (I_{12}) and the points corresponding to the assigned strike.

Note that Fig. 7(d) is equally applicable for wedge sliding situation. If the line of intersection of two discontinuity planes, I_{ij}, lie in the shaded area in Fig. 7(d), then the maximum safe cut slope angle corresponding to I_{ij} is 90°. Thus, the concepts shown in Figs. 7(d) and 8 should be used in estimating maximum safe cut slope angles under wedge sliding situation.



α: Moximum sofe cut slope ongle

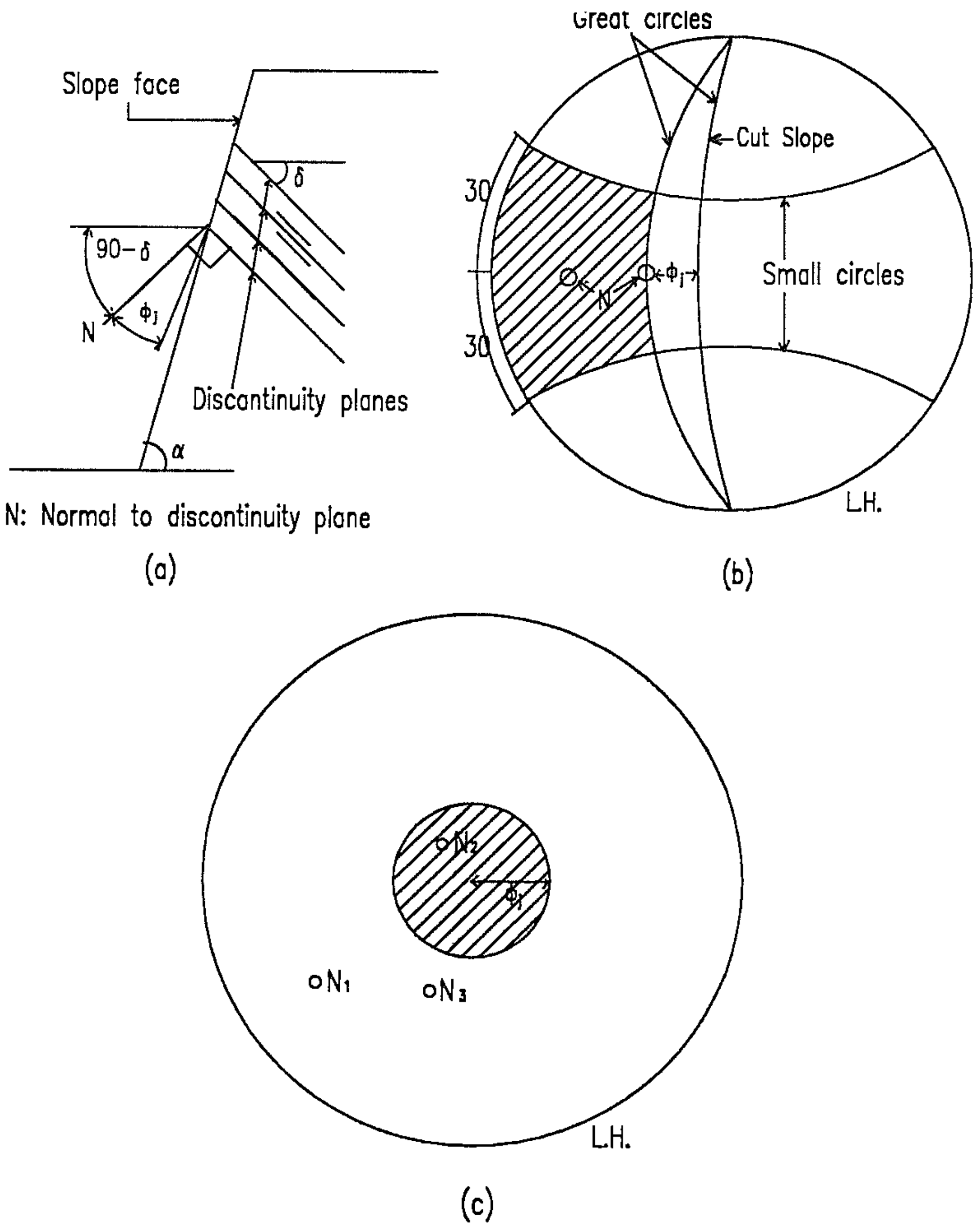
Figure 8. Stereographic construction to obtain the maximum safe slope angle for wedge sliding.

Toppling

Fig. 9 illustrates the kinematic analysis for toppling under gravity alone. Toppling can occur only if the discontinuities strike nearly parallel to the strike of the slope, say within 30°. In addition, discontinuity spacing should be low as shown in Fig. 9(a) to form thin layers of rock. For toppling failure, first it is necessary to initiate interlayer slip before large flexural deformations take place within the layers. If the layers have angle of friction ϕ_j, slip will occur only if the direction of applied compression (which is along the dip vector of slope) makes an angle greater than ϕ_j with the normal to the layers. If the cut slope is inclined α to the horizontal and the dip of discontinuity planes is δ, then the kinematic requirement for toppling is $(90-\delta) + \phi_j < \alpha$ as shown in Fig. 9(a). On a lower hemispherical stereographic projection, for toppling failure to occur, the normal vector N of the discontinuity should lie within the shaded area as shown in Fig. 9(b). The situation corresponding to the maximum safe cut slope angle occurs when N falls on the great circle which is ϕ_j degrees below the cut slope and striking parallel to it. Note that when N lies outside the two small circles shown in Fig. 9(b), the corresponding maximum safe cut slope angle is 90°. Also, it is important to note that toppling can occur only on discontinuities whose normals plunge at an angle less than $90-\phi_j$. That means with respect to the lower hemispherical stereographic plot shown in Fig. 9(c), if a normal vector of a discontinuity lies within the shaded area shown in Fig. 9(c), then the corresponding maximum safe cut slope angle is 90°. Thus, the concepts shown in both Figs. 9(b) and 9(c) should be used in estimating the maximum safe cut slope angles for toppling mode. Also, it is important to check whether the discontinuity geometry produces thin rock layers as shown in Fig. 9(a).

Results

Kinematic analyses were conducted using the mapped major discontinuities in the shiplock area to estimate maximum safe slope angles with respect to possible plane sliding, wedge sliding and toppling failure. Each major discontinuity was treated as a single feature. A computer code KINEM was developed to calculate maximum safe slope angles. Eventhough the mapped major discontinuities are shown in Fig. 5, some uncertainty exist concerning the actual extent of these discontinuities. Therefore, the kinematic analyses were conducted under two different cases as given below. For case 1, orientation of all the major discontinuities which appear on Fig. 5 were considered in the kinematic analyses. Under this case, indirectly, it was assumed that any major discontinuity appearing on Fig 5 has a possibility to cross the shiplock. Thus, results from these analyses can be considered to be on the conservative side. The major discontinuities which only crosses the shiplocks according to Fig. 5 were used in the kinematic analyses in the second case. If the major discontinuity map given in Fig. 5 is reliable, then these analyses should provide results closer to the reality.



* Maximum safe cut slope angle corresponding to N_2 is 90°
* Use construction given in Fig. 9(b) to estimate maximum safe cut slope angles corresponding to N_1 & N_3

Figure 9. Concepts related to kinematic analysis for toppling [Goodman(1989)] (a) a pictorial diagram. (b) on a stereographic plot. (c) influence of ϕ_j on maximum safe cut slope angle.

For Case 1 :

Plane Sliding. The maximum safe slope angle obtained for each major discontinuity is shown in Figs. 10(a) and (b), respectively for cut strike directions 111° (South-West shiplock face) and 291° (North-East shiplock face). The location of each bar shown in Fig. 10 corresponds to the actual location of the major discontinuity in the shiplock area. The starting and ending points of each bar represent starting and ending X coordinates of each major discontinuity. Note that X axis coincides with the strike of shiplock faces. Therefore, the location of each major discontinuity and the maximum safe slope angle corresponding to it can be identified from this diagram. Most of the bars in Figs. 10(a) and (b) indicate maximum safe slope angles between 65° and 90°. The results obtained for the whole shiplock region (disregarding the actual locations of major discontinuities) are shown through histograms in Fig. 11(a). Most of the maximum safe slope angles were found to be greater than 65°.

Wedge Sliding. For the wedge sliding mode, only the discontinuities which are located within a 50m distance were considered in calculating the maximum safe slope angles. Results for individual wedges are shown in Figs. 10(c) and (d). Similar to Figs. 10(a) and (b), each bar represents starting and ending X coordinates of each wedge. Figure 11(b) shows the histograms obtained for the maximum safe slope angle for the whole shiplock region disregarding the actual locations of the wedges in the shiplock area. For most of the wedges, maximum safe cut slope angles greater than 45° were obtained.

Toppling. It is not really necessary to consider toppling mode for the shiplock region since it is covered by a granitic rock mass. Toppling failures usually occur in layered rock such as slate, schist, and sedimentary rocks, and chances to form thin layers in a granitic rock mass are extremely low. Anyway, in this study, kinematic analysis was conducted for toppling. Due to the aforementioned reasons, these results should be considered as highly conservative estimates. Results for individual discontinuities are shown in Figs. 10(e) and (f). Figure 11(c) shows the histograms obtained for the maximum safe slope angle for the whole shiplock region disregarding the actual locations of the major discontinuities in the shiplock area. Most of the maximum safe slope angles for the toppling case were found to be greater than 85°.

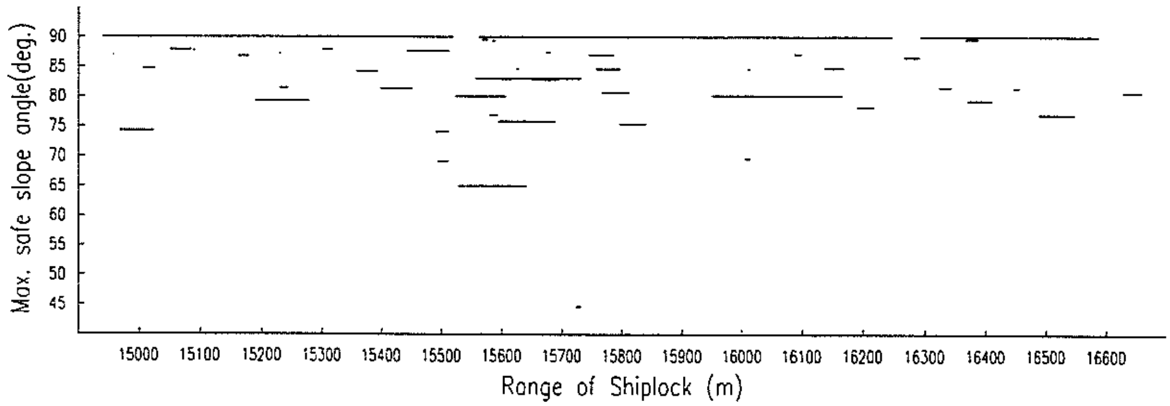
Table 1 Major discontinuity orientation data for different segments of the shiplock for case 2 kinematic analyses.

15150-15200(m)	Strike of SW Shiplock Face: 111°	
Discontinuity	Dip	Dip Direction
1. βu1020	82	316
2. F1062	60	326
3. F1061	75	351
4. F1067	80	46
15550-15600(m)	**Strike of NE Shiplock Face: 291°**	
Discontinuity	Dip	Dip Direction
1. F203	70	262
2. F204	82	45
3. βu1018	80	331
4. F1035	84	285
5. F8	80	247
15750-15800(m)	**Strike of SW Shiplock Face: 111°**	
Discontinuity	Dip	Dip Direction
1. βu1001	78	300
2. F1005	80	221
3. βu1002	80	325
4. βu1003	50	320
16080-16130(m)	**Strike of SW Shiplock Face: 111°**	
Discontinuity	Dip	Dip Direction
1. F205	65	269
2. F1009	80	274
3. F1011	70	101
4. βu1007	85	329
16420-16470(m)	**Strike of NE Shiplock Face: 291°**	
Discontinuity	Dip	Dip Direction
1. F1021	80	306
2. F1023	76	78
3. F1024	70	251
4. βu1009	78	90

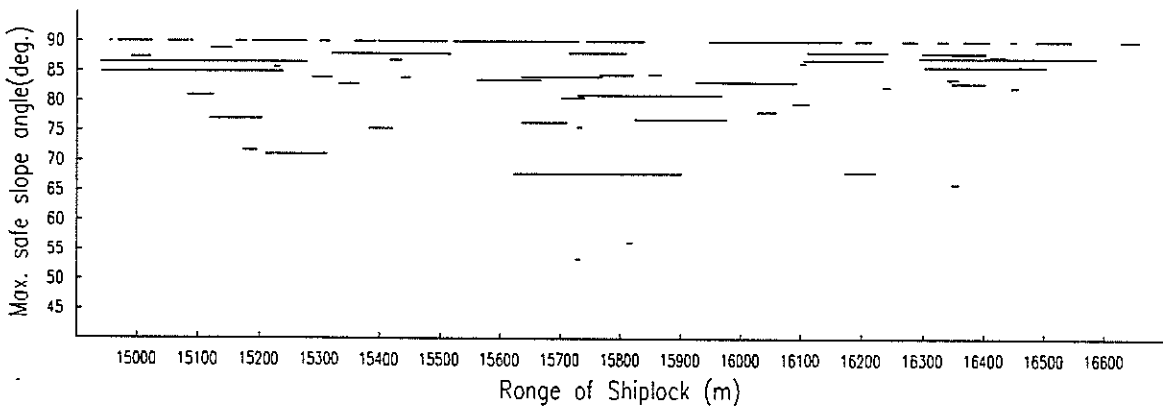
F: fault, βu: dyke
Orientations of Cut Slopes:
Strike of Cut (SW shiplock face) = 111°
Strike of Cut (NE shiplock face) = 291°
Dip Direction of SW shiplock face = 201°
Dip Direction of NE shiplock face = 21°

For Case 2 :

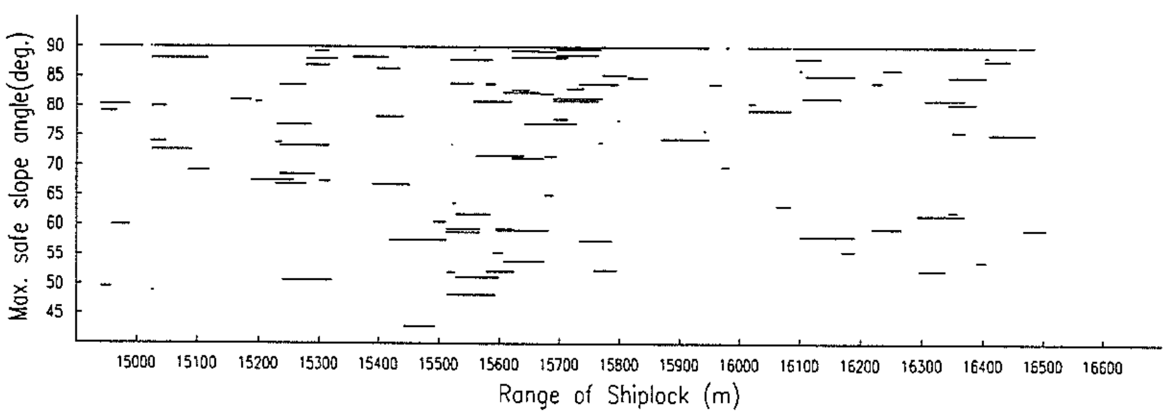
The total length of the shiplock (1750m) was divided into 50m segments. Those segments which do



(a) Plane Sliding - Cut Dir.=111°

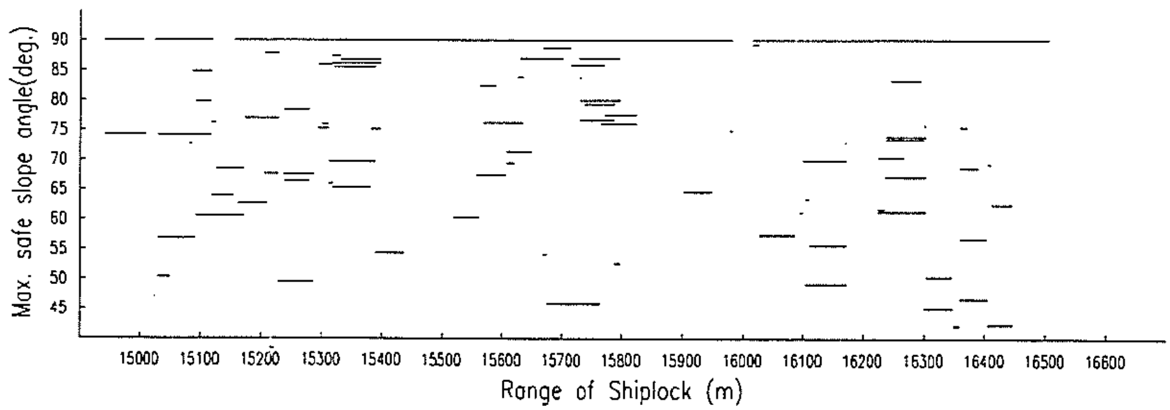


(b) Plane Sliding - Cut Dir.=291°

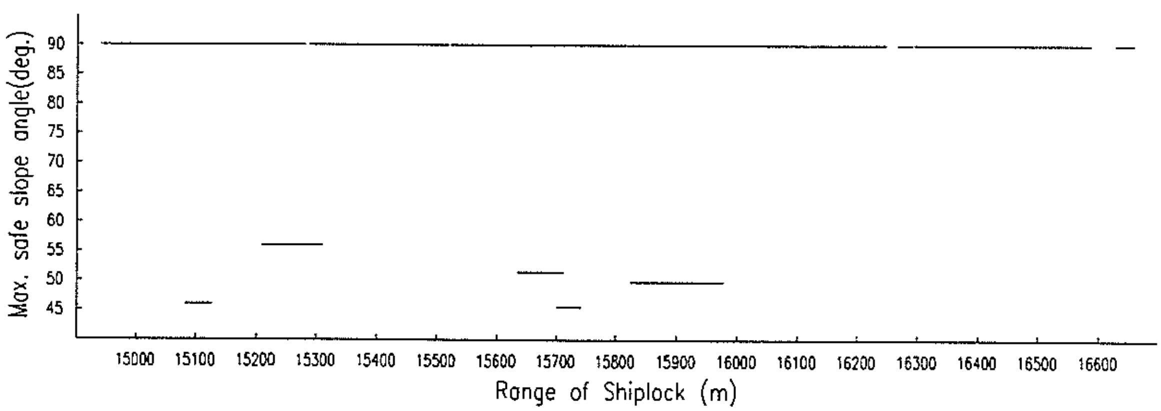


(c) Wedge Sliding - Cut Dir.=111°

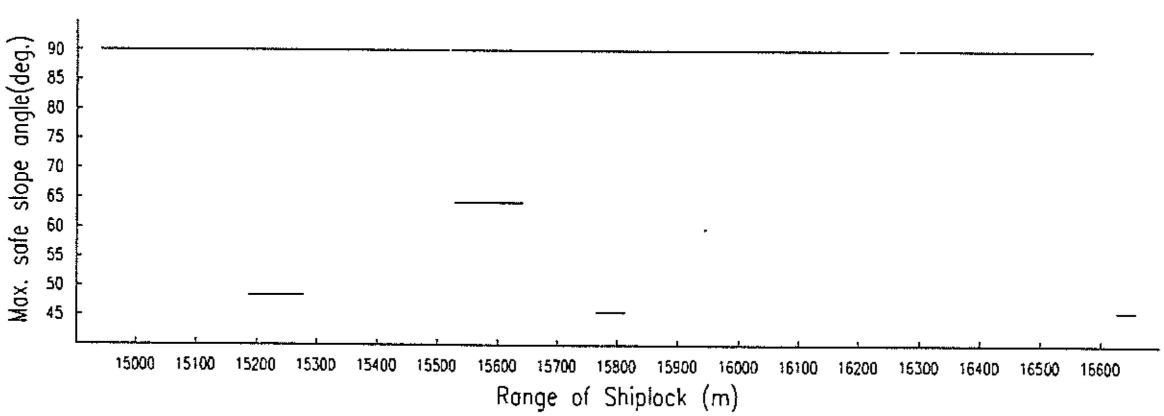
Figure 10. Maximum safe slope angles along shiplocks resulting from kinematic analyses conducted for case 1.



(d) Wedge Sliding - Cut Dir.=291°

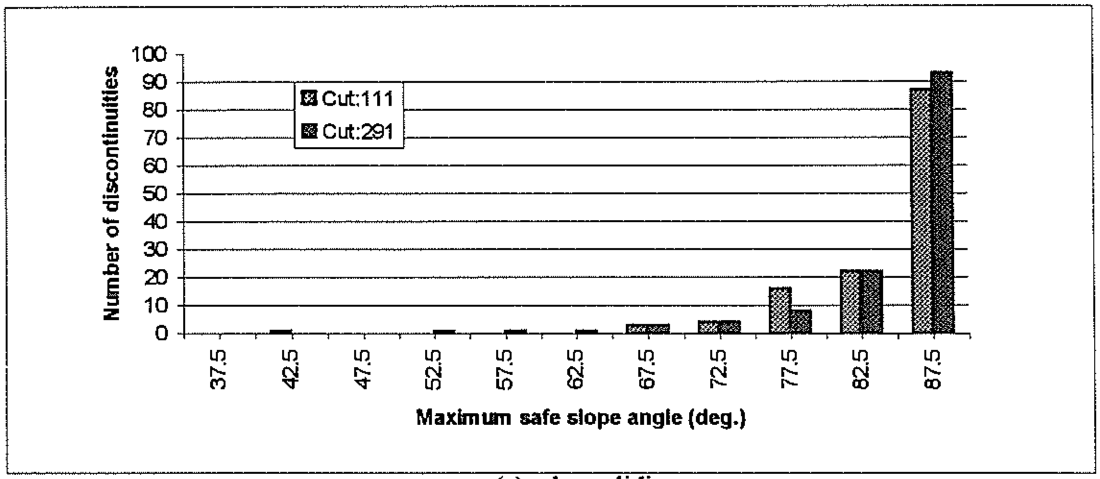


(e) Toppling - Cut Dir.=111°

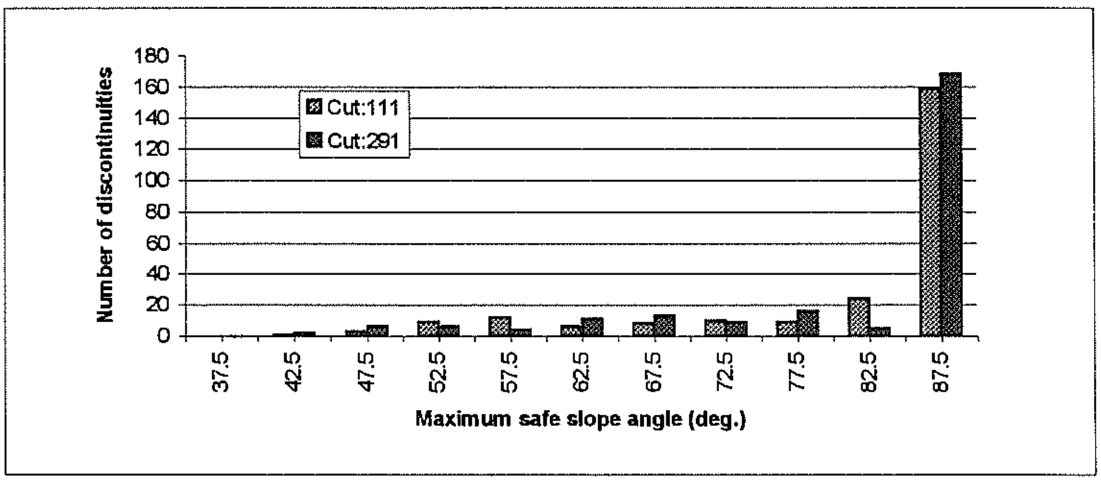


(f) Toppling - Cut Dir.=291°

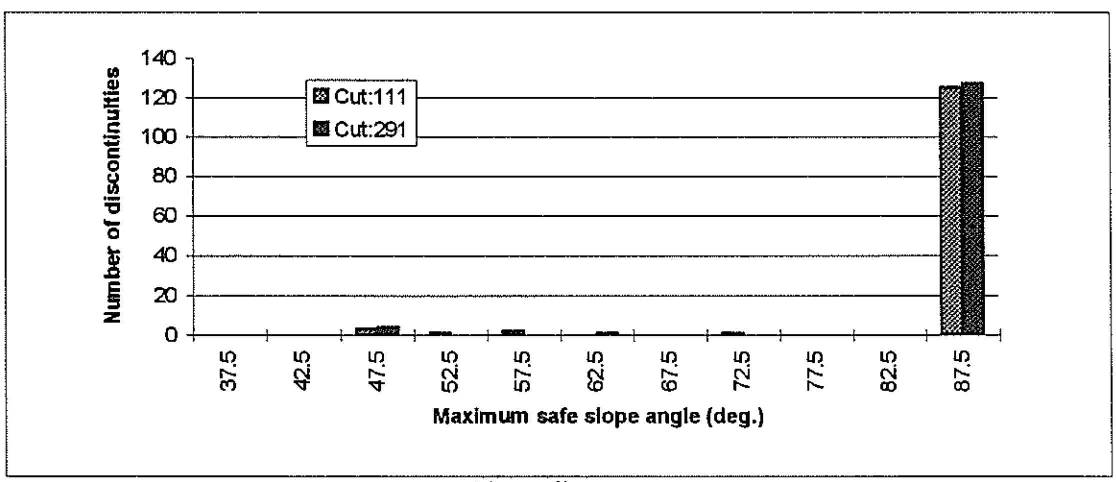
Figure 10. (Continued)



(a) plane sliding



(b) wedge sliding



(c) toppling

Figure 11. Histograms of maximum safe slope angle for different failure modes, based on kinematic analyses conducted for case 1.

not contain a potentially unstable block were not subjected to kinematic analyses. The kinematic analyses, therefore, were performed only for 5 segments where potentially unstable blocks were found. Table 1 gives the major discontinuities and their orientations for the segments which were subjected to kinematic analyses. Note that analyses were performed separately for the SW shiplock face (strike of cut 111°) and for the NE shiplock face (strike of cut 291°). The maximum safe cut slope angles obtained for plane sliding, wedge sliding and toppling modes for these different segments are given in Table 2.

Conclusions

Kinematic analysis for plane sliding has resulted in maximum safe cut slope angles greater than 65° for most of the discontinuities. Kinematic analysis has produced maximum safe cut slope angles greater than 45° for most of the wedges. For the wedge sliding mode, only the discontinuities which are located within a 50m distance were considered in obtaining the maximum safe slope angles. Maximum safe cut slope angles greater than 85° were obtained for most of the discontinuities in the toppling case.

According to the results obtained for both cases 1 and 2, it seems that the shiplock faces in the proposed permanent shiplock region in fresh rock are more or less stable up to a cut slope of about 45°. It is important to keep in mind that this conclusion is based on the kinematic analyses performed using only the major discontinuities. In the future, kinematic analyses should be performed incorporating both major and minor discontinuities. Also, it may be worthwhile to perform kinematic analysis based on the block theory and compare the results obtained through block theory against the results obtained through the traditional kinematic analyses conducted in this study.

All the analyses conducted in this study limited the loading on the rock mass to gravitational forces only. Therefore, some kinetic analyses should be performed incorporating possible water forces, earthquake forces, etc.

Table 2 Maximum safe slope angles for different failure modes in different segments of the shiplock region resulted from case 2 analyses.

Location (m)	D_1	D_2	D_3	D_4	D_5	T_1	T_2	T_3	T_4	T_5	I_{12}	I_{13}	I_{14}	I_{15}	I_{23}	I_{24}	I_{25}	I_{34}	I_{35}	I_{45}
15150-15200	90	90	90	90	-	90	90	90	46	-	90	90	90	-	80.7	90	-	90	-	-
15550-15600	90	82.7	83.5	90	90	90	90	90	90	90	65.8	90	90	67.4	79.4	78	65.2	82.5	90	90
15750-15800	90	80.6	90	90	-	90	90	90	90	-	84.1	89.7	90	-	84.9	90	-	90	-	-
16080-16130	80.1	87	90	90	-	90	90	90	90	-	90	90	71.7	-	90	86.1	-	90	-	-
16420-16470	87.4	82.3	90	85.6	-	90	90	90	90	-	62.4	90	57.8	-	90	75.3	-	90	-	-

D_1: For Plane Sliding along Fault 1
D_2: For Plane Sliding along Fault 2
D_3: For Plane Sliding along Fault 3
D_4: For Plane Sliding along Fault 4
D_5: For Plane Sliding along Fault 5
T_1: For Toppling on Fault 1 (ϕ_j=35°)
T_2: For Toppling on Fault 2 (ϕ_j=35°)
T_3: For Toppling on Fault 3 (ϕ_j=35°)
T_4: For Toppling on Fault 4 (ϕ_j=35°)
T_5: For Toppling on Fault 5 (ϕ_j=35°)

I_{12}: For Sliding on Planes 1 and 2 Along I_{12}
I_{13}: For Sliding on Planes 1 and 3 Along I_{13}
I_{14}: For Sliding on Planes 1 and 4 Along I_{14}
I_{15}: For Sliding on Planes 1 and 5 Along I_{15}
I_{23}: For Sliding on Planes 2 and 3 Along I_{23}
I_{24}: For Sliding on Planes 2 and 4 Along I_{24}
I_{25}: For Sliding on Planes 2 and 5 Along I_{25}
I_{34}: For Sliding on Planes 3 and 4 Along I_{34}
I_{35}: For Sliding on Planes 3 and 5 Along I_{35}
I_{45}: For Sliding on Planes 4 and 5 Along I_{45}

Article below

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