IN THE HIGH COURT OF JUDICATURE AT BOMBAY

ORDINARY ORIGINAL CIVIL JURISDICTION

WRIT PETITION NO. 904 OF 2005

Ehsanul Haque A. Nadvi ...Petitioner

Versus

Union of India and others ...Respondents

Mr. Akhilesh Upadhyay for the petitioner.

Mr. B.A. Desai, Additional Solicitor General, with Ms. Naveena Kumari, for respondent No.1.

Mr. Abhijeet Wagh, instructed by Uttangale & Co., for respondent No.3.

Mrs. Shobha Ajitkumar for respondent No.6.

Mr. Thakore Jariwala for respondent No. 9.

WITH

WRIT PETITION NO. 123 OF 2006

Gavdevi Durga Devasthan Trust ... Petitioners

Versus

The Union of India and others .... Respondents

Mr. Rajan Jaykar, instructed by Mr. S.S. Salunke, for the petitioners.

Mr. B.A. Desai, Additional Solicitor General, with Ms. Naveena Kumari, for respondent No.1.

Ms. Bharti Mahant for respondent No.3.
Mrs. Shobha Ajitkumar for respondent No.4.

Mr. Thakore Jariwala for respondent No. 7.

Mr. Anirudh Joshi with Mr. Deepak Poonamiya, instructed by A.V. Jain Associates, for respondent No.8.

CORAM: **H.L. GOKHALE, Ag. C.J.,** &
V.M. KANADE, J.

DATE: **FEBRUARY 14, 2007**.

P.C.

On the last date of hearing, we had asked the Slum Rehabilitation Authority ("SRA") as to what is the exact distance between the SRA project and the hills. SRA has not filed an affidavit till date. Mr. Wagh, holding for Mr. Uttangale, seeks further time. The Municipal Corporation was also to inform the Court as to what are the rules regarding the construction around such hills. Ms. Shobha Ajitkumar informs on behalf of the Corporation that there are no such specific rules.

2. A report is received from the Engineers appointed who informed the Court about the strength of the hill. All parties may obtain copies of the report at their own expenses. Matter to stand over to 14th March, 2007, by which date a reply ought to be filed by SRA and the petitioners may file their rejoinder on receiving the reply.

2. As far as Petition No. 123 of 2006 is concerned, necessary amendment be carried out within one week and copies be supplied to

Mr. Joshi, appearing for respondent No.8, who may file his reply to the petition. The Engineers, who have submitted the report, have also furnished their bills for the professional services rendered. It comes to about Rs. 5 lakhs. Mr. Joshi and Mr. Jariwala are agreeable that their clients will bear Rs.2,50,000/- each. The said amount would be deposited by the next date of hearing. The deposit will be subject to the orders to be passed finally in these matters.

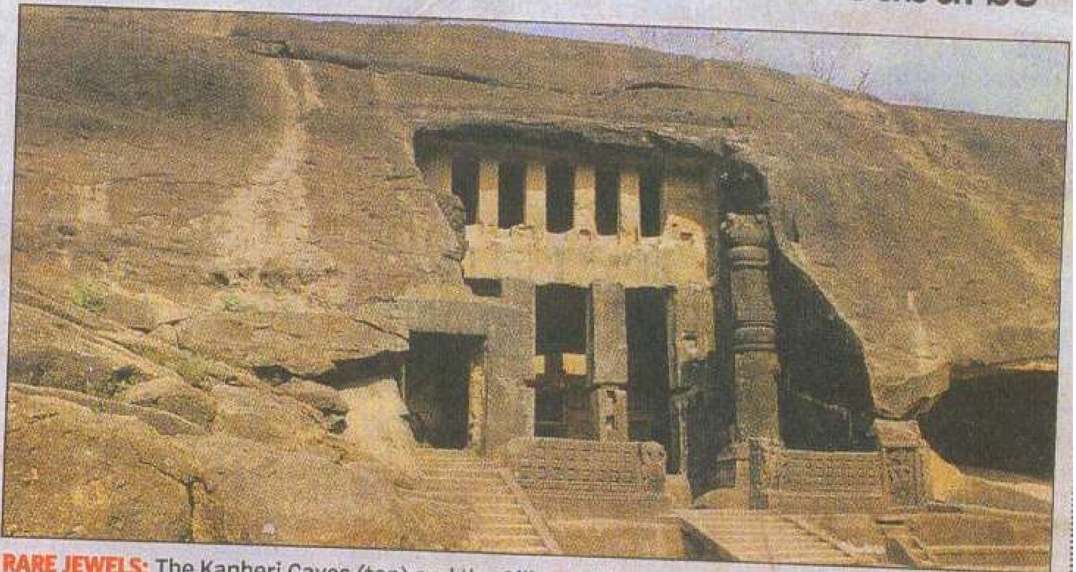
ACTING CHIEF JUSTICE

V.M. KANADE, J.

Heritage list gets longer

New Entrants Include Parsi Baugs, Structures In Suburbs

Anjali Joseph | TNN



RARE JEWELS: The Kanheri Caves (top) and the Gilbert Hill at Andheri may also make it to the list

Mumbai: In what could be a turning point for heritage conservation in the city, the proposed new heritage listing has broadened the scope of what might be termed Mumbai's heritage. Entries on the new list span the eastern and western suburbs as well as the island city.

Open spaces including Shivaji Park, Marine Drive and Chowpatty are included, as are Mumbai's forts at Sewri, Worli and Mahim. Hindu and Buddhist caves at Kanheri, Mandapeshwar, Jogeshwari also come into the new list and so do some of the chawls and Parsi baugs (colonies) that came up in the first half of the last century. The list proposes to add around 1,100 structures and open spaces to the 1995 list, and is the result of five years of work by six groups of architects and planners.

Unusual structures including the natural column of black basalt at Gilbert Hill, Wadala, thought to be around six million years old, have also been added. Gilbert Hill is a proposed Grade I in the new list, which would mean no development could be carried out there without prior permission being obtained from the heritage committee. A 17th-century Portuguese footbridge in Dahisar is also listed.

But sources involved in the process say the list, which will now be scrutinised by a panel which includes MMRDA commissioner T Chandrashekhar and BMC commissioner Johny Joseph, may be whittled down before being notified. "This could be considered an ideal list, but it's likely that in the wrangling over what stays and what goes, a good percentage of the current recommendations will be either downgraded or removed," said one of the architects involved. After being approved by MMRDA, final approval for the list rests with the civic chief.

Heritage experts warn the new list shouldn't be allowed to moulder on the shelves of the state government's Urban Development department as earlier recommendations and guidelines have done. While the BMC and state occasionally allocate money to restore specific buildings, officials have in the past sided with 'pro-development' lobbies and resisted implementing regulations to protect Mumbai's heritage spaces and structures.

"Since 2003 the heritage committee has recommended several additions for notification by the Urban Development department. These include guidelines for Marine Drive, Cuffe Parade, Khodadad Circle, Cumballa Hill precinct, Matharpakhadi and Khotachiwadi precincts, Mahalaxmi precinct, Opera House precinct and others. The textile mill list was sent to the BMC earlier this year with a second list of 425 structures still pending notification, but the BMC and UD department have just sat on every proposal," said a member of the heritage committee.

As well as the remains of Mumbai's mill heritage, the new list includes other industrial architecture, for example, in the docks. Instances of chawls and group housing societies (Parsi baugs and Hindu colonies) that shaped the city's development at the turn of the nineteenth and twentieth centuries are also featured.

New grade I structures include the Royal Opera House (previously listed as Grade IIA) as well as the forts at Sewri, Mahim and Worli.

A significant number of open spaces has been added. These include Marine Drive sea front, the Girgaum Chowpatty beach, the Sunni, Bohra, Catholic and Jewish cemeteries at Worli; the grounds of the Islam, Hindu, Wilson College, Grant Medical College and Police Gymkhanas at Chowpatty, Shivaji Park in Dadar, the cemetery of St Michael's church in Mahim, the Mahatma Gandhi maidan at Worli and the Ismail Yusuf College campus at Jogeshwari.

Among places of worship, Mahim *dargah* is listed as grade I, with the complex surrounding it as grade II-A. Several suburban agiaries and churches also make the grade.

The structures featured in the 1995 list have also been reviewed. This means that several structures are upgraded from Grade III to Grade IIA or B: these include Wilson College (now grade IIA) and the Mahakali temple in the Mahalaxmi temple precinct.

Many private residences have been added in order to protect a now threatened part of Mumbai's history. Some were already on the list, like the Birla house on Malabar Hill where Gandhi often stayed.

Page 1

Exhibit 6
(10-18)

REPORT ON THE GEOLOGICAL INVESTIGATION OF THE AREA AROUND GILBERT HILL, ANDHERI, MUMBAI.

by
Dr. S. F. Sethna
Consulting Geologist

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January 30, 2007

REPORT ON THE GEOLOGICAL INVESTIGATION OF THE AREA AROUND GILBERT HILL, ANDHERI, MUMBAI.

The geological investigation at the above mentioned site has been undertaken on the request of Dr. S. Y. Mhaiskar (Principal, Sardar Patel College of Engineering) and Mr. Cyrus R. Tata (Sr. Civil and Soil Engineer) who have been appointed by the Honourable High Court, Mumbai, to look into various aspects regarding damage caused to Gilbert Hill and suggest measures for protecting the hill.

Location and Topography:

The Gilbert Hill is situated west of the Andheri Railway station (WR). The topography of the hill is in the form of a practically vertical monolith that rises at least about 60 meters above the surrounding ground level. The hill displays beautiful vertical columnar jointing which can be considered as a Geological monument worth preserving and may be made into a Tourist attraction site.

General Geology:

The geology of the area is part of the Deccan Volcanic Province, which is made up of a number of subaerial basaltic lava flows that occur as practically horizontal flow basalts. The Deccan Volcanic Province extends over a very large area covering the major part of Maharashtra State and also extends into the

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neighbouring states of Gujarat, Madhya Pradesh, Andhra Pradesh and Karnataka and was formed about 65 to 67 million years before present. There are mainly two types of lava flows, viz., (a) Simple Lava flow basalt and (b) Compound lava flow basalts. Some of the simple lava flow basalts that are generally made up of compact basalt, display hexagonal columnar joints (fractures developed due to contraction of the rock which solidifies at above 1000° C and thereafter undergoes contraction during the cooling process) that are usually restricted to the upper and lower part of the flow basalt. They are generally described as the Upper Colonnade Zone and the Lower Colonnade Zone with an intermediate zone that does not display columnar jointing that is described as the Entablature Zone. The Compound lava flow basalts invariably show amygdaloidal character, with the gas cavities (vesicles) filled up by secondary minerals such as, zeolites, calcite, chlorite and silica. Such lava flow basalts do not display columnar jointing.

In the western coastal part the lava flows show a westerly dip varying from 5° to 15°. Moreover in the western coastal belt around Mumbai, Salsette and Bassein the lava flows show subaqueous character in the form of spilitic pillow lavas and subaqueous flow breccias and tuffaceous breccias that are described as hyaloclastites (Sethna, 1999). Sedimentary intertrappean beds, such as shales, which are even fossiliferous, often separate these subaqueous lava flows. In addition, to the extrusive flow basalts and hyaloclastites, there are a number of intrusive bodies mainly in the form of dykes of dolerite and basalt (Sethna et al, 1994 & 1995) as well as some trachytic and granophyric intrusives along with some rare types of alkaline rocks, such as lamprophyres and nepheline syenites. Majority of the dykes along the western coastal belt, extending from Balsar in the north to Murud-Janjira in the south, show a north-south trend.

30/1/2004

Geology at the Site:

The plot under investigation is situated in the west central part of Salsette Island, about 500 meters west of the Andheri Railway Station (Suburban Western Railway). The rock type encountered in the Gilbert hill is mainly compact basalt which is intrusive into the stratified tuffaceous breccia that shows distinct westerly dip (Photo 1). The basalt intrusion is in the form of a nearly circular body that was originally much larger (Photo 2) in diameter as compared to what is remaining now in the form of a practically vertical monolithic body that rises almost 60 meters above the surrounding ground (Photo 3). Similar columnar jointed intrusive basalt also outcropped in Amboli Hill, west of Jogeshwari Railway Station. The later intrusive body has been described by Tolia & Sethna (1990) as a lopolithic intrusion. Unfortunately the entire basalt outcrop at Amboli Hill has been quarried and now there are only a few traces of the basalt seen in the area. There is no evidence of the Gilbert hill basalt being a lopolithic body, as we only see the vertical cylindrical body **which represents a volcanic plug.**

The basalt plug of the Gilbert hill shows very distinct columnar jointing that extends from the top to the bottom of the hill. The jointing is very well exposed in the western, northern (Photo 4) and eastern parts (Photo 5) of the hill. In the southern part of the hill there is some amount of rolled down debris that covers the exposure of the columnar jointing (Photo 6). The present extension of the basalt plug is restricted to the Gilbert hill while in the surrounding areas there are outcrops of the stratified tuffaceous breccia or hyaloclastite. The Gilbert Hill basalt has been dated by Dr. Mike Widdowson, of the Open University, Milton Keynes, U.K. (personal correspondence) and it is 60.5 ± 1.2 million years old.

30/1/2007

Proposed Project:

The proposed project envisages the preservation of this majestic geological monument that is one of its kind in India. A similar old volcanic plug showing columnar jointing also occurs in New Mexico, and is described as "Ship Rock", that outcrops in the American desert.

Conclusions :

It is very necessary to preserve this majestic monument as it is one of its kind in India and there should be a small garden made around the hill with a plaque giving its age and nature of the geological structure that it represents. It can be made into a place of tourist attraction. The engineers can decide on measures to be taken to preserve the existing monument and prevent it from being damaged by the forces of nature.

S F Sethna
30/1/2007

Dr. S. F. Sethna

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Sethna, S. F. & Mortaza Mousavi (1995) Basic intrusives in the Deccan Trap along the West Coast flexure zone. ***"Dyke swarms of Peninsular India" ed. T. C. Devaraju, Mem., Geol. Soc. India, No.33***, pp.365-374.

Sethna, S. F. (1999) Geology of the Mumbai and Surrounding Areas and its Position in the Deccan Volcanic Stratigraphy, India. ***Jour. Geol. Soc. India***, V.53, No.3, pp.359-365.

Tolia Nita & S. F. Sethna (1990) Lopolithic intrusion of Basalt in the intertrappeans at Amboli Hill, Jogeshwari, Bombay. ***Jour. Geol. Soc. India***, V.35, No.5, pp.524-528.

SFS

Description of Photographs

Photo No.1 Westerly dipping stratified tuffaceous breccia – Hyaloclastite.

Photo No.2 Photograph taken by Prof. R. N. Sukheswala in early 1960s that shows another monolith of Columnar Basalt just north of the present outcrop.

Photo No.3 Present outcrop of the monolith showing columnar jointing, seen from a distance.

Photo No.4 Columnar joints seen in the northern part of the monolith.

Photo No.5 Columnar joints seen in the eastern part of the monolith while going up the stairs to the temple.

Photo No.6 Rolled down debris that covers the columnar joints in the southern part of the monolith.

30/1/2007

By Richard E. Goodman[1] and D. Scott Kieffer[2]

Exhibit 7 (19-

ABSTRACT: The behavioral modes to which a rock slope is susceptible are many and complex. This article discusses a long but not exhaustive list of common failure styles, highlighting observable characteristics that distinguish one from another. Slopes in both strong and weak rock masses are considered. Principles are stated to explain how and why different failure modes develop in different rocks. The discussion is illustrated with examples of diverse failure modes in foliated metamorphic rocks developed in the walls of an eroded spillway runout.

INTRODUCTION

The geotechnical engineer has an abiding interest in rock slopes, as part of the natural environment and terrain in which he or she works, or as a vital part of a work to be constructed above or below ground. Natural rock slopes form the foundations of surface penstocks and buildings, and the abutments of bridges and dams. Artificial rock slopes are products of excavations to create space for transportation routes, buildings, powerhouses, dams, and portals. These are "permanent" slopes in which rock movements have to be prevented or controlled. But even "temporary" slopes, as for quarries and contractor's operations, may have portions in which failure needs to be prevented for a long time. Some slopes intended to be short-lived have taken up new lives as permanent features of the landscape abutting on housing or industrial developments.

In examining rock slopes while driving through mountainous terrain, it may seem as if hanging ledges with open joints and ready-to-slide blocks are detachable parts of the mountain that are just as likely to drop into the roadway as not. Unfortunately, determining whether this is true is not easily amenable to analysis, and despite computer simulations and stability analyses, there is often uncertainty that stability will have been assured unless adequate stabilization measures have been constructed.

For design, it is helpful to be acquainted with and be able to recognize the diverse ways in which slopes in rock masses can fail. Because rock structures and compositions vary within wide limits, the variety of behavioral styles is rich. Textbooks tend to oversimplify the wide spectrum of failure modes to facilitate the education of newcomers to the field. Those who have practiced in varied geologic terrain will readily recognize this strategy and adopt their own wiser and broader approach to real problems. But those who lack varied experience may try to establish simple models of behavior where more complex modes are at work, with less than comforting results.

This paper describes a longer list of common failure styles and calls attention to observable characteristics that distinguish one from another. Slopes in hard and soft rocks are considered, although retaining this distinction can be difficult in some earth materials for which the difference between soil and rock is blurred, particularly near the surface. Examples of several rock slope failure modes developed along a dam spillway in the Sierra Nevada foothills are reviewed to illustrate the diversity of slope behavior that can exist even in a single locality.

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[2]Sr. Engr., Jacobs Associates, 500 Sansome St., 7th Floor, San Francisco, CA 94111.

Note. Discussion open until January 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on June 14, 1999. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126, No. 8, August, 2000. ©ASCE, ISSN 1090-0241/00/0008-0675–0684/$8.00 + $.50 per page. Paper No. 21229.

ROCK SLOPE ENVIRONMENT

It must be appreciated that the rock slope environmen distinctly different and generally less secure than the und ground environment. Although a person may feel more posed underground because of the dangers of working i closed space, the surface excavation tends to be less sta because in situ stresses are lower, the rocks are weathered, water is a more active agent. The continuous flow of tangen stress around a carefully excavated underground opening te to retain blocks in place in the walls and roof, whereas li or no surface traction operates on the faces of blocks at surface where the tangential stress is usually small. Furth more, block theory shows that the key blocks that can mo into a surficial excavation are larger than the maximum k blocks of an underground gallery so that local failures tend be larger on the surface than underground. Surface excavatic usually include variably weathered rocks whose strengths m be considerably less than that of the intact rock and that w

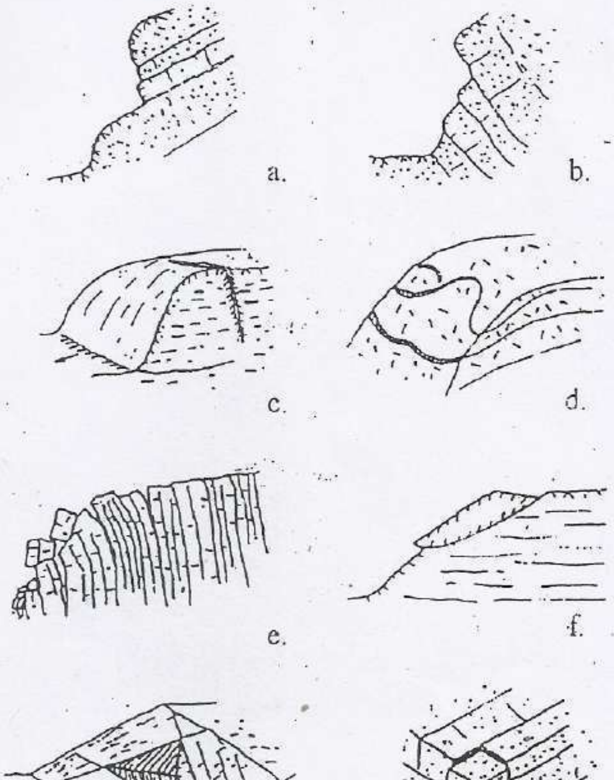

FIG. 1. Some Indicators of Potential Slope Hazard

during construction and thereafter under the action of water, ice, and chemical reactions in warm and moist climates.

Although water flows tend to be intercepted in the underground and surface excavation, surficial materials may yield far more subsurface water due to an increased degree of fracturing and greater permeability. Surface waters further compound the troubles that ground water can present to the surface excavation. In the underground and surface environments, the hydraulic pressure of water in fractures and internal pore pressures within soil-like porous fault gouge, fissured rocks, or soft sedimentary rocks, can markedly destabilize a rock mass. During rain storms, surface cuts may also have to contend with effects of loss of capillarity or softening of clay minerals, while internal or external erosion of silty sediments and saprolite can trigger rapid slope destruction.

RECOGNITION OF ROCK SLOPE HAZARDS

Within a rock mass exposed to view, certain observable features warn of potential hazard, and others of hazard already developed. Fortunately, most slope problems materialize during the construction period and can be rectified with appropriate redesign or construction expedience, especially if the failure mode is properly identified. However, others may develop only after a long time, during which successive stages in a progression of events slowly and surreptitiously move the slope toward danger or eventual collapse.

shown in Fig. 1(a), it follows that what once covered thi surface has been removed. That simple observation identific the particular structural feature as a proven slide or releas feature. The blocks that moved from the surface might hav done so by erosion, sliding, or rotation. The agents that cause this may have vanished long ago, but the detail always merit inspection. Similarly, discontinuities arranged in a stair stepped configuration, as shown in Fig. 1(b), suggest that previously overlying columns had toppled there in the past, possibly during construction, and therefore identify a toppling tendency if the geometric conditions that foster it are rejuvenated.

Various kinds of tension cracks can be recognized in slopes Movements of a deformable block along a preexisting or a new shear surface, as shown in Fig. 1(c), may open one or more linear or arcuate ground cracks. In sheet-jointed granite or massive sandstone formations, arcuate tension cracks precede slab detachment and "arches" form where slabs release in tension. In both instances, the formation of the tension crack means that the resisting force previously sustained by tensile stresses in the rock slab have been lost, and replaced by increasing shear resistance on the underlying sliding surfaces. In base friction models, it is possible to observe the additional sliding and internal deformation simultaneously with the formation of the tensile crack. Incipient movement of a sliding block will open along joints and separate from these "release

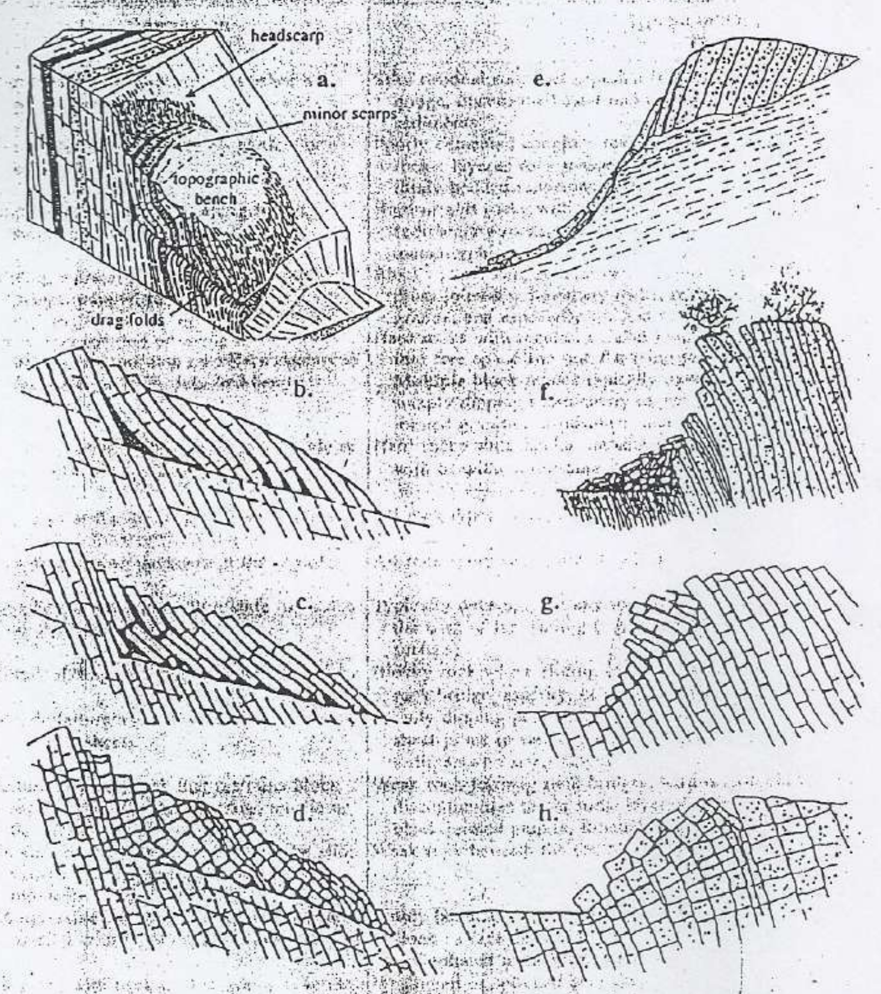

FIG. 2. (a–e) Rock Slumping; (f–h) Toppling

surfaces, as shown in Fig. 1(h). In this case, the opening of joints replaces the formation of new tension cracks in unjointed materials, but the results differ in that there will have been no automatic increase in the shear stress on the sliding plane since the releasing joints never carried any tensile stress.

Different modes of rock and soil slope behavior leave characteristic fingerprints. For example, toppling failures, as shown in Fig. 1(e), produce not only deep "V"-shaped ground cracks between adjacent toppling beds, but upslope facing exposures of the tops of the layers, which Goodman and Bray (1977) have called "obsequent scarps." Topping failures also produce a toe region of broken rock that resembles talus. Block slumping, described later, produces upward opening, "A"-shaped cracks above the lower seat of sliding [Fig. 2(b)]. Classic soil-type slumping failures, as shown in Fig. 1(f), with backward rotational motion, produce conspicuous head scarps, as well as overthrusting near the slope toe. Movement of individual joint-bounded rock blocks leaves negative expressions of these blocks in hollows within the rock slope, as shown in Fig. 1(g), which Hatzor and Goodman (1995) have termed "moulds." The latter identify combinations of discontinuity surfaces that have actually intersected at a point in space within the rock mass to delimit real removable blocks. If these blocks had moved under the natural forces still operating in the slope, the moulds identify the key blocks of the critical joint con tions. This is useful since there are sometimes many dif discontinuity sets that could theoretically intersect to for portant blocks.

MECHANISMS OF ROCK SLOPE FAILURE IN DIFFERENT ROCK MASS TYPES

The idealized, simple failure modes featured in mos books on rock mechanics [e.g., Hoek and Bray (1981); man (1989)] are: (1) block sliding on a single face (som termed slab sliding; (2) block sliding on two faces si neously along their line of intersection (often termed sliding); and (3) overturning of multiple columns (u called toppling). "Textbook cases" in which one of thes behavior styles is the sole cause for rock slope damage occur. Block and wedge sliding modes are more commo toppling, but the latter is very significant, if not domin some rock types of steep mountain slopes or open pit Table 1 describes these failure modes, and additional complex modes of rock slope failure, and gives exam typical materials in which they are realized.

If a rock slope is large and embraces a mix of rock and structures, it cannot be expected that a single m

TABLE 1. Some Modes of Failure of Slopes in Rock Masses

Failure mode (1)	Description (2)	Typical materials (3)
Erosion, piping	Gullies formed by action of surface or ground water	Silty residual soils and saprolite (especially disintegrated granite), silty fault gouge, uncemented sand rocks, uncemented noncohesive pyrclastic sediments
Ravelling	Gradual erosion, particle-by-particle or block-by-block	Poorly cemented conglomerates and breccias; very highly fractured hard rocks; layered rock masses being loosened by active weathering, e.g., thinly bedded sandstone/shale
Block sliding on a single plane	Sliding without rotation along a face; single or multiple blocks	Hard or soft rocks with well defined discontinuities and jointing, e.g., layered sedimentary rocks, volcanic flow rocks, block-jointed granite, foliated metamorphic rocks
Wedge sliding	Sliding without rotation on two nonparallel planes, parallel to their line of intersection; single or multiple blocks	Blocky rocks with at least two continuous and nonparallel joint sets (e.g., cross-jointed sedimentary rocks, regularly faulted rocks, block-jointed granite; and especially foliated or jointed metamorphic rocks)
Rock slumping	Backward rotation of single or multiple blocks, moving into edge/face contact to form one or more detached beams	Hard rocks with regular, parallel joints dipping toward but not daylighting into free space and one flat-lying joint that does daylight into free space. Multiple block modes typically develop in foliated metamorphic rocks and steeply dipping sedimentary rocks; single block modes develop in block-jointed granitics, sandstones, and volcanic flow rocks
Toppling	Forward rotation about an edge—single or multiple blocks	Hard rocks with regular, parallel joints dipping away from the free space, with or without crossing joints; foliated metamorphic rocks and steeply dipping layered sedimentary rocks; also in block-jointed granites
Slide toe toppling	Toppling at the toe of a slide in response to active loading from above	All rock types susceptible to block toppling
Slide head toppling	Toppling behind the scarp at the top of a slide	All rock types susceptible to block toppling
Slide base toppling	Toppling of beds beneath a slide mass due to shear across their tops	Typically developed in any rock type susceptible to toppling, located beneath the base of landsliding (e.g., where the seat of sliding occurs along a fault surface)
Block torsion	Rotary sliding in a single plane	Blocky rock where sliding on the potential slip surface is prevented by a rock bridge, asperity, or other restraint which forms a hinge
Sheet failure	Tensile failure and fall or sliding of hanging sheets	Steeply dipping preexisting sheet joints in granitics and sandstones; new sheet joints in weathered rocks, friable massive sandstones, and pyroclastic sediments on steep slopes
Rock bridge cracking	Failure of intact rock that restrains block motion, through compressive, tensile or flexural cracking	Weak rock forming rock bridges; hard or soft rocks with impersistent discontinuities (as in some layered sedimentary rocks, volcanic flow rocks, block-jointed granite, foliated, or jointed metamorphic rocks)
Slide base rupture	Rupture of the rock mass beneath the slide caused by slide-transmitted shear and moment	Weak rock beneath the toe of a slide
Buckling and kink band slumping	Compressive collapse of columns or slabs parallel with the rock slope face	Thinly bedded, weak sedimentary rocks inclined steeply and parallel to the slope surface; shale-sandstone and shale-chert sequences, coal measures, and foliated metamorphic rocks
Soil-type slumping	Shearing with backward rotation, as in clay soils	Weathered or softened clay shales; thick fault gouge; altered zones; soft tuffs. High pore pressure zones
Rock bursting	Hard rock under breaking stress	Granite and marble quarries into highly stressed rock. Hard sedimentary rock at the base of deep, narrow canyons

failure will cover all sectors. On the contrary, within a single sliding mass it is not unreasonable to find more than one of the simple failure modes at work. One part may be sliding, another toppling, another experiencing erosion, and yet another suffering from new fractures and destruction of previously continuous rock volumes. Principles governing compound behavior of actual rock slope failures are discussed in the following section.

Principles Favoring Different Modes of Failure

1. Finite blocks are formed by the intersections of existing discontinuities and the excavation surface(s).
2. Adversely oriented blocks move out first, leaving behind a new space into which adjacent blocks can move; the first blocks to move are termed "key blocks" (Goodman and Shi 1985).
3. Sliding along an adversely oriented rock face or block edge will invariably occur if the kinematic conditions for such sliding are met. The most important of these conditions is that the block be removable in the excavated space, meaning that the direction of incipient motion daylights into the excavation.
4. If sliding motion is prevented or inhibited, rotational movements are favored. Thus when sliding opportunities are blocked because the sliding layers do not daylight, toppling, buckling, block slumping, or torsional fail may occur.
5. Incomplete blocks that would tend to slide, but tha not completely delimited by the joint system may when new rock fracturing completes the isolation of block.

These principles were applied in the ordering of Tabl which is discussed methodically in the following section.

Discussion of Different Failure Modes Listed in Table 1

Erosion can very seriously degrade a rock slope, eithe the surficial action of concentrated runoff, or from inte erosion and piping, particularly in poorly cemented silty s iments, highly weathered granitic rocks and saprolite. Inte erosion and piping can occur when natural or artificial slo contain loose silty materials in contact with open-jointed h rock, an arrangement that occurs in many volcanic rock se and in major fault zones. If the erodible soils lie beneath r with open joints, exiting seepage can start a process of ra erosion, which undermines adjacent rocks by modifying shape of the free surface. If the erodible soils are above open joints, their internal erosion into the cracks is possi but generally less damaging to the slope (although it may devastating to upstream structures).

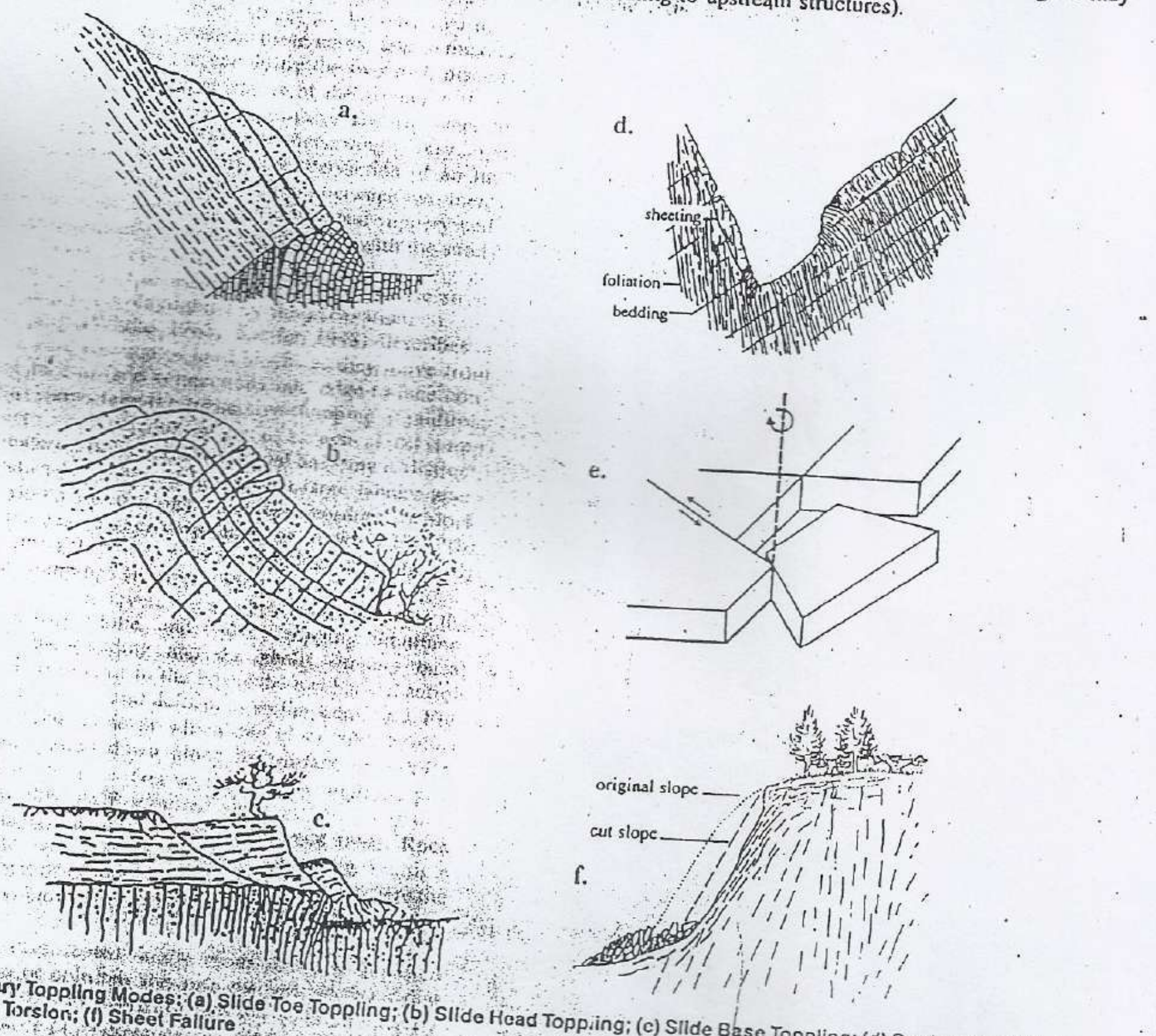

FIG. 3. Secondary Toppling Modes: (a) Slide Toe Toppling; (b) Slide Head Toppling; (c) Slide Base Toppling; (d) Contrasting Slide To Topples; (e) Block Torsion; (f) Sheet Failure

page 2

Ravelling refers to progressive loosening and erosion of cobbles or blocks from the surface of the rock cut. It is a process of mass wasting and gradual erosion under active weathering and gravity transport. Very highly fractured hard rocks, for example, columnar basalts and brittle sandstones lying atop soft shales, may contribute large talus cones by ravelling. Depending on the slope geometry, particles may become projectiles during the ravelling process.

Block sliding on a single plane of weakness can occur only after the perimeter of the eventual sliding mass has been completely delimited. In the case of a layered rock mass with one dominant discontinuity set, a potential slide cannot occur unless the lateral margins of the block are carved out by topographic valleys, or have developed strike-slip type shear ruptures. The latter is facilitated by the occurrence of individual faults or shear zones that cut the slide mass roughly parallel to the direction of the dip of the siding surface. Blocks defined by three or more sets of joints do not require any other structures or topographic aids to slip from the slope if they are "removable" in the excavated space. A simple test of removability, determined by Shi's theorem, is one of the significant contributions of block theory, as discussed by Goodman (1995). Blocks shown to be removable may slip in a direction on one face alone, or on two intersecting block faces by moving along one of the block's edges, or they may move in rotational modes as will be enumerated.

Wedge slides occur in convex slopes cut by only two nonparallel discontinuity surfaces. In these cases, approximately four-sided sliding blocks are carved by the two rock discontinuity planes and two tangent planes of the ground surface. Thus, no additional lateral release surfaces are necessary to isolate the block as it prepares to slide. Accordingly, very large sliding masses can be set free by the intersection of an important shear zone or fault, with a contact between two members or formations, or any other well-developed slippery bedding plane. An engineer or geologist entrusted with the safety of rock slopes must keep an alert eye on the developing geologic map of a project to assure that such an adverse structural intersection is not daylighted by the excavation.

Rock slumping (Wittke 1965; Kieffer 1998) describes a mode of backward rotation of hard blocks as they move from their original face-to-face connections into edge-to-face contacts. Fig. 2(a) shows how the successive slumping of multiple blocks produces a scar resembling that of a classical soil slump in its gross features; however, the internal anatomy is distinct, with independent back-rotated blocks and large tabular apertures. Rock slump morphology changes according to block stiffness and the degree of cross-jointing, as shown in Fig. 2(b) (flexural slumping), Fig. 2(c) (block slumping), and Fig. 2(d) (block flexure slumping) (Kieffer 1998).

In all three cases, the layers are blocked from sliding on the steeply dipping beds alone, and end up slipping simultaneously on both the bedding and the gently dipping basal crossing joint. This assigns to the layers the mechanical action of beams, which fracture and deform as sliding continues. Fig. 2(e) shows a similar mode in which one block after another has slumped and rafted down along the surface of a softer lower layer. Without subsurface exploration, it might be possible to mistake this block-armored slope as belonging to a single homogenous unit of a layered hard rock mass. Rock slumping is the analogue to toppling, involving multiple blocks in a process of progressive slope destruction, where the layers do not dip into the rock but rather dip toward the free face.

Toppling is a deep-seated failure mode for rock slopes in which the blocks or columns dip into the hillside, such that any single layer tends to overhang and is supported only by the passive resistance of its downslope neighbors. Fig. 2 shows three classes of toppling failures—flexural toppling [Fig. block toppling [Fig. 2(g)], and block flexure toppling 2(h)]—named by Goodman and Bray (1977) according t role of cross joints.

The result of toppling failure is comparable in some to a well-known form of soil creep that yields a hinge i shallow depth. To the authors, however, the term "creep" nifies slow, quasi-continuous motion under constant stress does not normally lead to rupture. Toppling failures on other hand can be deep, large, and potentially rapid, and involve fresh rock well below the domain of true geol creep. Like any landslide mass, the period of rapid move is preceded by slowly accelerating displacements as the weight is gradually redistributed to the toe blocks. After main rupture event, the now flexurally broken rock mass tinues to progress downslope, and in this condition is d aging to structures like penstocks that had been ignora placed atop the toppled mass. Both rock slumps and top can produce steep talus fronts of highly broken and very lo rock blocks that can menace lower facilities.

Slide toe toppling, a "secondary toppling mode" (Good and Bray 1977), occurs when layers are blocked from slid by a toppleable toe mass, as shown in Fig. 3(a). In effect, is a two-block active-passive mechanism in which the pass region yields by toppling, rather than by sliding. In the sl on the right side of the valley of Fig. 3(d), the definition

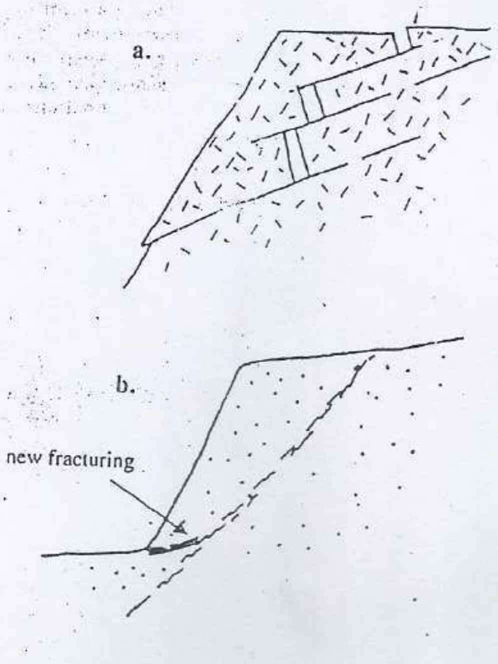

FIG. 4. Additional Modes Involving Rock Fracturing: (a) Rock Bridge Cracking in Tension; (b) Rock Bridge Failure in Compression; (c) Slide Base Rupture

the active block is incomplete because of a rock bridge at the toe, and the passive block is comprised of phyllite dipping into the slope, in the classical manner for toppling under self-weight. However, on the left side of the valley in Fig. 3(d), an active block composed of weathered phyllite moving along a sheet joint at shallow depth bears against a passive block with closely spaced foliation joints dipping steeply into the valley bottom. Note that the toppling toe forming the passive block in this case could not topple under gravity alone as the columns comprising this block were not initially overhanging.

Slide head toppling and *slide base toppling* are additional secondary toppling modes. Slide head toppling [Fig. 3(b)] may occur in the new space created at the top of a slide by its displacement. In slide base toppling [Fig. 3(c)] the horizontal shear stress transmitted along the base of an incipient slide provokes toppling of steeply dipping layers forming the foundation for the slide toe.

Block torsion [Fig. 3(e)] is a failure mode of a single block in which local restriction of sliding causes the block to spin about a hinge at the point where sliding is impeded. As sliding is stopped, the block moves in a rotary motion along one contacting surface. Such a failure mode could surprise a constructor who pinned a block too near the hinge (or whose pin actually created the hinge). Blocks can also rotate about a corner, without sliding on any plane, although examples have not been reported. Wittke (1984) and Mauldon and Goodman (1990) discuss analysis of these types of rotational failures.

Sheet failure describes failure of sheets bounded by newly formed or previously existing extension joints formed parallel to and at shallow depths beneath the ground surface. Classic sheet joints that preexist a rock cut in granitic rocks and massive sandstones may create hanging slabs if the cut parallels the original slope surface. New sheet jointing, which tends to form in any relatively unjointed, hard or soft rock parallel to a newly cut steep slope, has the same effect. In either case, if the inclination of the sheet joint is steeper than the angle of friction between the joint walls, as is so often the case, the slope is stable only by virtue of tensile stresses at the tops of the steepest portion of the sheets, which are in effect left hanging. New tensile cracks then allow sheets to detach. Weathering of the sheets reduces the tensile strength and thereby promotes tensile cracking and slab detachment. Fig. 3(f) depicts failure of a hanging sheet formed beneath a new cut slope. This type of slide is particularly dangerous because failure occurs suddenly. If the slope is high, the volume of material may be large despite the thinness of new sheets.

Rock bridge cracking allows the final step in the isolation of some slide blocks that otherwise would have failed soon after initial excavation. Because of the finite extent of most joints, very large and potentially significant slides may at first be incompletely outlined by the joint system. After excavation gradual crack growth concentrates stresses of increasing intensity in the remaining unfractured portion of the bridge, leading to an accelerated rate of movement and eventual throughgoing rupture. In Fig. 4(a), direct tensile cracks link up short parallel joints to form a piecewise continuous sliding surface. In Fig. 4(b), crack growth crushes and destroys the toe of a rock slope with a nondaylighting shear surface. Similarly, growing flexural cracks may connect nonpersistent joints to facilitate large toppling failures.

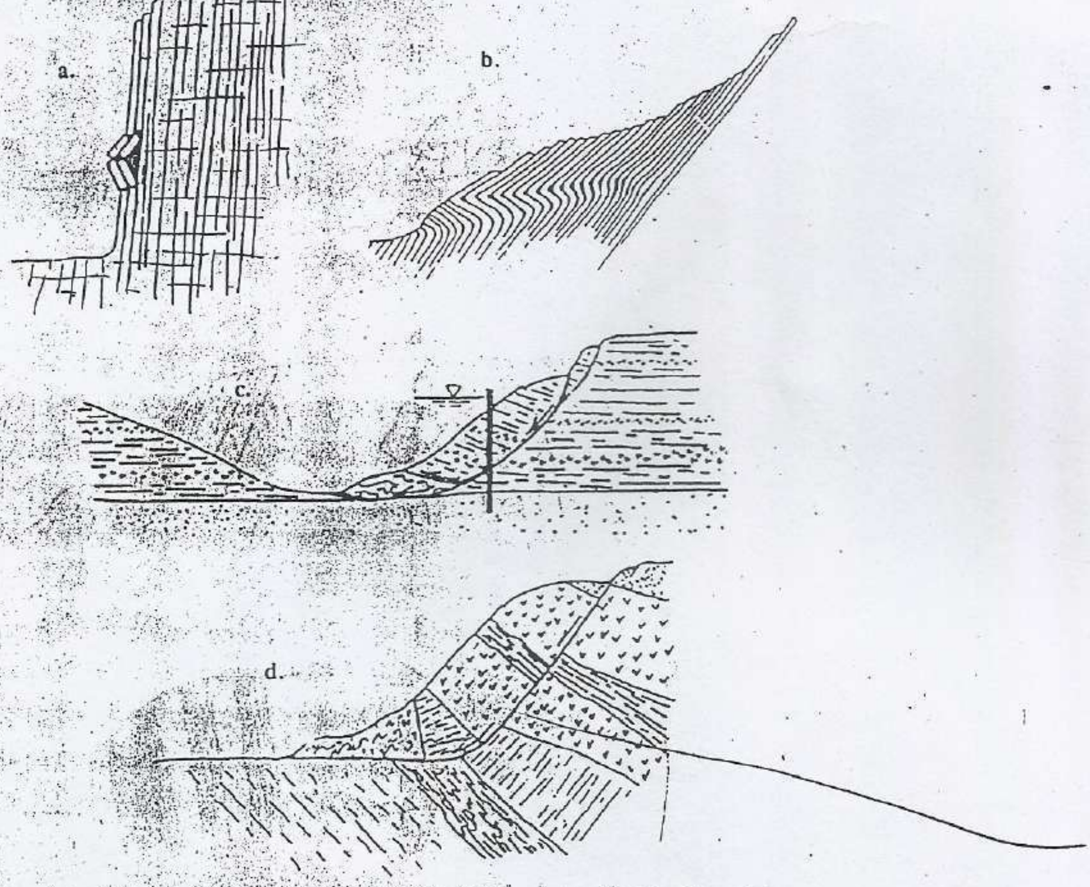

FIG. 5. (a) Buckling; (b) Kink Band Slumping; (c–d) Soil Type Slumping

Slide base rupture [Fig. 4(c)] involves fracture and failure of weak rock underlying a slide block. In the case depicted, the shear stress transmitted beneath the toe induces tensile splitting of the rock forming this member. Weakening and destruction of the toe can propel a previously creeping slide mass toward global failure.

Buckling (column collapse) describes compressional failures of thin rock columns or slabs in the rock face [Fig. 5(a)]. Initiation of collapse takes advantage of some initial imperfection in the layer, for example, a minor flexure or material weakness in the region of critical stress (Cavers 1981). Fig. 5(b) shows a mode of failure intermediate between rock slumping and buckling, termed *kink-band slumping* (Kieffer 1998).

Soil-type slumping, with backward rotation achieved through shear along a curved failure surface, is found only in rock masses that are sufficiently soft and relatively free of weak seams or joints. Rock types that may generate slumps are typically clay-rich rocks, softened by loosening and wetting, as, for example, smectite-rich clay shales and altered tuffs. Slumps can also occur in highly fissured rocks containing so many discontinuities as to be effectively homogenous, as may be found in and adjacent to major fault zones and among tertiary sediments and coal-bearing rock formations. In most other rocks, fracture tends to develop in the tensile mode rather than by shear rupture, so that classical curved shear surfaces prove to be uncommon. Fig. 5(c) depicts a style of slumping found in rock formations in which the sliding material is uplifted by water pressure in an underlying aquifer that has impeded drainage in the valley bottom. The principal cause of the failure is high pore pressure in the sliding mass, which acts as an aquiclude. Fig. 5(d) depicts a related case where the high pore pressures are caused by an impervious member at the base of the slope, which impounds ground water beneath the hillside.

The final entry in Table 1, *rock bursting*, refers to failure of rock near the free surface due to high tangential stresses. This mode differs from the formation of sheet joints previously described, in that fracture growth and rock destruction are dynamic events. Rock bursting occurs typically in hard-rock quarries in highly stressed regions, but can also happen when excavating rock slopes at the base of a deep, narrow steep-walled canyon in hard rock.

This itemization of failure modes is nonexhaustive. Among the additional behavioral modes that have been recognized are various types of slides with interacting multiple blocks, folded rock masses that break up into several smaller blocks after incipient motion, and masses that topple or slide because of very deformable soil or rock in the toe of the slope.

DISCUSSION OF STABILITY ANALYSIS PROCEDURES

In order to judge the most likely potential failure modes, the basic tools are structural engineering geological mapping, the measurement of piezometric levels and springs throughout the slope, and measurements of slope deformations (with slope inclinometers and precise surveying of fixed surficial targets). Once the modes have been appreciated, the degree of safety can be judged using 3D statics with free-body diagrams deduced from the geological map and water forces calculated from the piezometry. Limit equilibrium computations using block theory programs are particularly applicable to single block slides of complex 3D shape. Block theory determines the strong influence of the direction of the cut slope on the mode of slope instability. Two-dimensional limit equilibrium

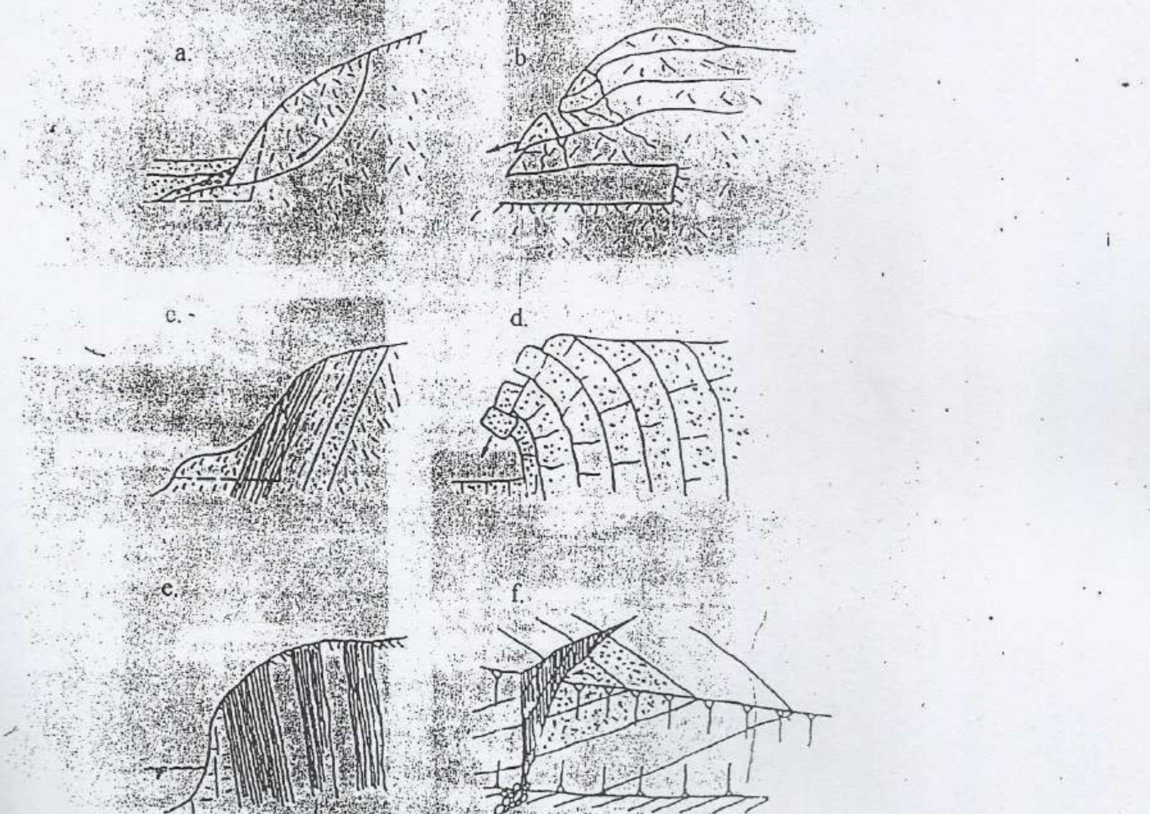

FIG. 6. Some Kinematic Causes of Rock Slope Failures

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methods developed for soil slopes are only occasionally applicable to rock slope problems. With 2D modes like toppling, rock slumping, and simple block sliding, numerical models that include the representation of discontinuities prove useful. Studies of this type are within the capabilities of, for example, UDEC, DDA, and FLAC (Cundall and Hart 1993). The numerical approach allows the modeler to compare the relative cost effectiveness of different remedial schemes, or to judge the likelihood that erosion, excavation, or deformation will trigger global slope failure. Goodman and Bray (1977) presented a limit equilibrium analysis for toppling slopes, and Ke et al. (1994) extended the analysis to handle drag of soil over the rock surface and water pressures between the blocks. Kieffer (1998) developed a limit equilibrium analysis for multiple block slumping.

KINEMATIC CAUSES OF ROCK SLOPE FAILURE

Among the causes and triggers of rock slope failures, as discussed by Terzaghi (1959, 1963), the authors find it helpful to distinguish a class of *kinematic causes*. As opposed t "causes" that alter the stress state in a potentially sliding mass these involve changes in spatial relationships that set up nev directions of allowable block motion. Kinematic causes ar erosion or excavation events that critically alter geometri boundary conditions of an incipient slide. In Fig. 6(a), fo example, excavation of sediments and previous slide materi completes the isolation of the toe of a preexisting rock slid In Fig. 6(b), the driving of a large tunnel beneath a daylightin shear surface causes a chain of events that release block slide in the slopes above. Mining work in the toe of a steep slop can similarly release slides or topples (as in the famous Turt Mountain slide near Frank, Alberta). Fig. 6(c) depicts the cas where a new excavation in the side-hill daylights the slidin surface of a new block slide. In Fig. 6(d), continued dee seated toppling of a mountain creates new block slides throug a gradual steepening of the dip of cross joints. Fig. 6(e) show a common condition along a rocky coast where bombardme by waves and erosion of the toe of sea cliffs removes t

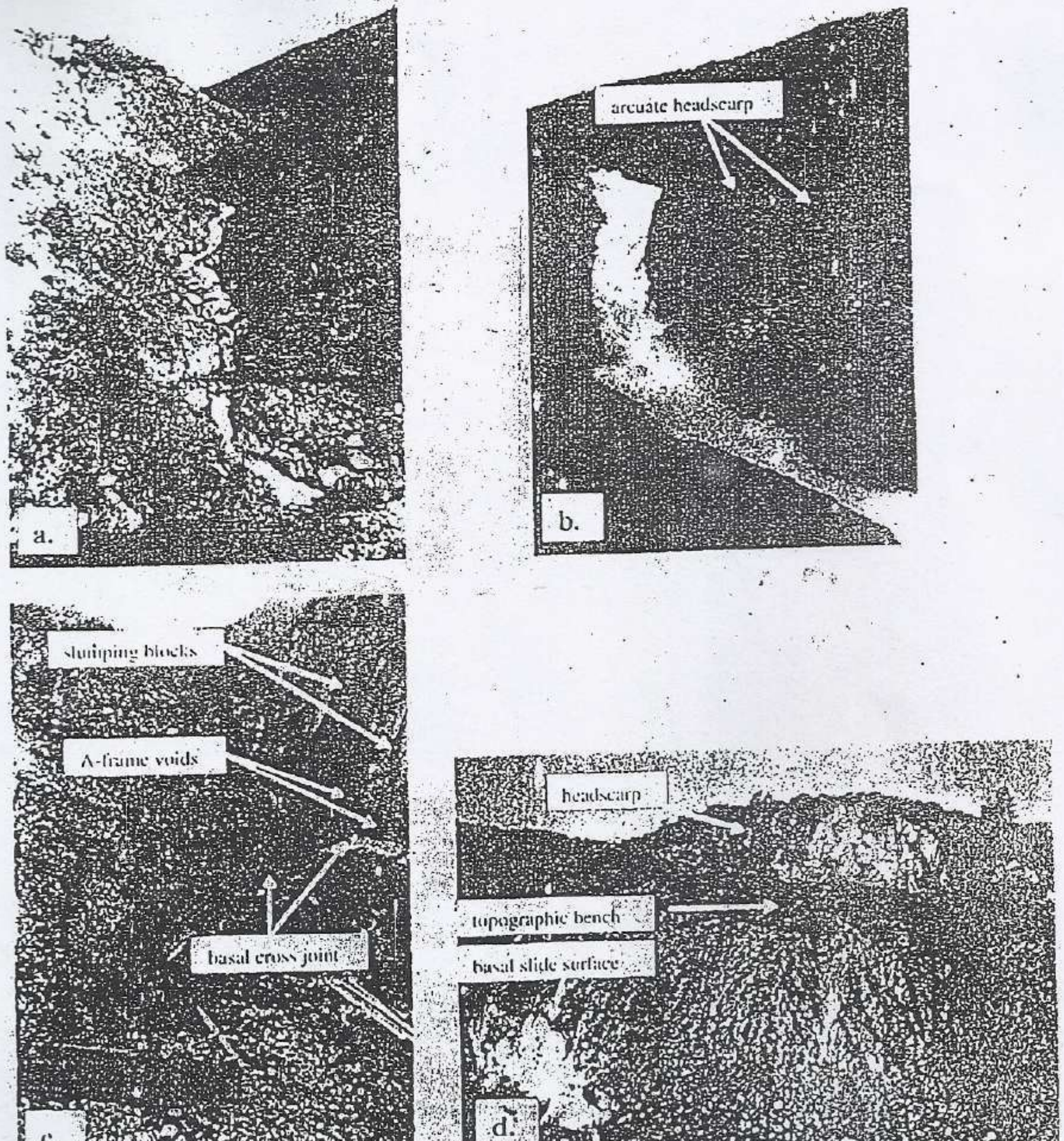

FIG. 7. Rock Failure Modes Exhibited in Eroded Runout Canyon of Pardee South Spillway

essential support from a potentially toppling or slumping mass. Similarly, wave erosion can provoke slumps and slides by redefining the boundary conditions along the toe. Fig. 6(f) shows how erosion of a gully can isolate potential wedge slides. This is a less well-appreciated kinematic cause that deserves careful attention. Erosion of a gully not only removes supporting earth and changes hydrologic conditions, but it reconfigures the rock slope and enlarges the free space. Block theory can be used to judge how potentially damaging this can be in any particular case.

ROCK SLOPE FAILURES ALONG SPILLWAY OF PARDEE DAM, CALIFORNIA

Failure modes developed along a spillway in the Sierra Nevada of California illustrate the diversity of behavioral styles to which a rock slope is susceptible. The Pardee Dam, constructed across the Mokelumne River in the late 1920s, has a separate overflow spillway structure and apron on blocky jointed metavolcanic rocks. About 100 m downstream of the apron, the discharge turns abruptly to follow a natural drainage (Mexican Gulch) cut into slate and phyllite bedrock with steeply inclined foliation striking subparallel to the channel axis. Years of flooding have eroded a deep bedrock canyon along the entire runout whose walls have failed in various translational and rotational modes. The rock mass structure is dominated by the foliation, which results in footwall and hanging wall slope geometries along opposing sides of the channel. The rock mass and its structure can readily be establishe susceptible to rock slumping and rock toppling failures.

Fig. 7(a) depicts spillway channel conditions prior to flo ing in 1930. Fig. 7(b) shows a multiblock slump along right side of the channel developed after five years of dov cutting. Fig. 7(c) at the toe of this failure shows that h. rotations of neighboring blocks have occurred by "kick out" along the gently dipping basal cross joint, a "fingerpri of block slumping. The larger rock slump (approximately m high) shown in Fig. 7(d) has undergone complex inter deformation but detailed mapping, facilitated by natural e sion exposing a section through the slide mass, confirmed t rock slumping is the underlying failure mechanism.

A typical example of block flexure toppling along the sp way hanging wall is shown in Fig. 8(a). Slender columns c ated by the foliation have produced impressive forward ro tion and flexure above the hinge line. Fig. 8(b) shows example of slide toe toppling developed along the spillw footwall, at the toe of the rock slump of Fig. 7(d). The p dominant failure modes in the spillway canyon walls are tc pling along the spillway hanging wall and rock slumping the spillway footwall, as depicted in base friction model te [Fig. 8(c)]. Field conditions observable in the spillway and t behavior of base friction models suggest the general rule th slopes across an excavation or valley from those susce tible to rock toppling should be evaluated for rock slumpi and vice versa. Rock slumping in the spillway canyon th

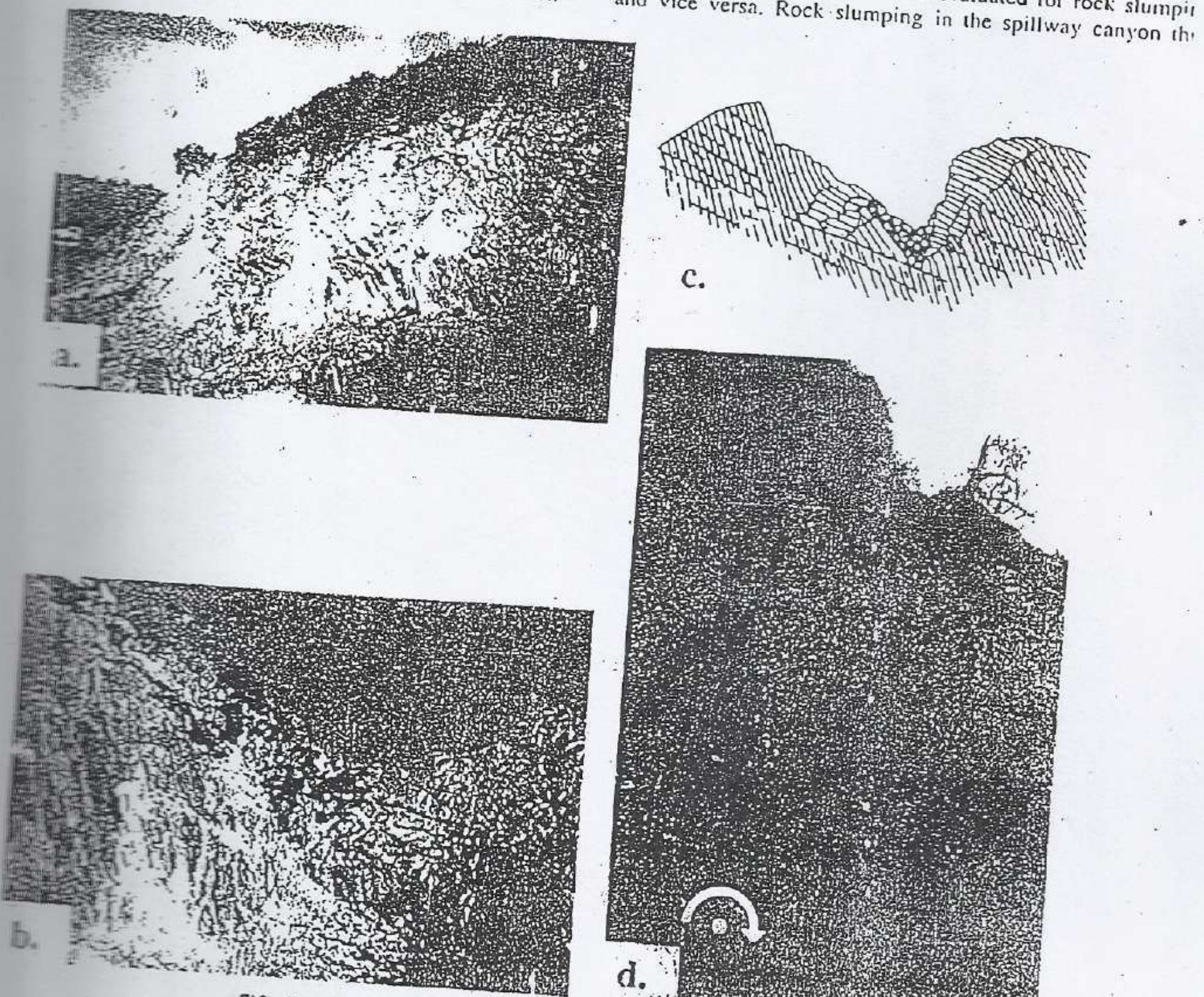

FIG. 8. Rock Slope Failures in Runout of Pardee Spillway

represents an important analogue, or "cousin" to rock toppling.

Block sliding, wedge sliding, buckling, and block torsion failures are also exhibited in the spillway canyon. A block torsion failure along the spillway footwall is shown in Fig. 8(d) in an eroded reentrant of the canyon wall. Sliding along the steep foliation surfaces is kinematically inadmissible since they do not daylight, but slabs of rock could rotate about a hinge at the block toe, inducing rotary sliding along the foliation plane.

DISCUSSION

The problems of rock slopes are seen to be capable of much more variation and complexity than generally represented. The goal here was not to provide an adventure for classification fanatics, but to acknowledge the broad spectrum of behavioral modes to which a rock slope is susceptible, particularly when we excavate the rock or place structures on sloping ground. Classification in this sense is as potentially useful to the engineer as Karl Terzaghi's appreciation of the different kinds of clay soils has been to the soils engineer. As Terzaghi wrote to R. L. Loofbourow in 1953, "how are you going to describe what you know about the physical properties of rocks and how can you correlate your experiences with those of others if you have no adequate language in common?"

In the field we can see the rock trying to express what is happening to it. We would not wish to prescribe medicine based on a faulty diagnosis, especially if we neglected even to examine the patient. However, in making this examination, we need to heed Terzaghi's counsel to Adolph Ackerman concerning the observations of deformations in the Serre Penstock slope (Goodman 1999): "The man in charge of the field observations should always keep in mind that field observations could as well be performed by a recording machine unless the findings produce reactions in the brain of the observer and are utilized as tools for improvement and clarification of ideas."

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