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RESERVOIR-INDUCED LANDSLIDES

GLISSEMENTS DE TERRAIN CAUSES PAR DES RESERVOIRS

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Summary

Slope movements induced by reservoirs involve various types of movement and geologic materials. Because they may be large and very rapid, rock slides related to reservoirs generally have been considerably more destructive than slope movements in surficial materials.

The Grand Coulee Dam impoundment, Franklin D. Roosevelt Lake on the Columbia River in the United States, has been the site of hundreds of reservoir-induced landslides since filling of the reservoir in the early 1940's. These slides occurred, and are still occurring, in unconsolidated Pleistocene glaciofluvial materials which constitute much of the rim of the reservoir. Another interesting case study on the Columbia River is provided by the Downie Slide in Canada. This 1500 million m^3 prehistoric rock slide is of considerable importance because it will be situated on the bank of a major reservoir that is still in the planning and construction stage.

In the United States, impetus has been given to dam safety programs by the recent failures of Teton and Toccoa Dams. Although these failures did not result from landslides of the reservoir rims, the increased awareness of the importance of dam safety has also spurred national interest in landslides that constitute hazards to reservoirs and dams.

Résumé

Les mouvements de pente causés par un réservoir mettent en jeu quelques types variés de mouvements et de matériaux géologiques. Les glissements des rochers près des réservoirs, à cause de leur grandeur et leur vitesse de mouvement, ont en général produit plus de destruction que des mouvements de pente des matériaux superficiels.

Au lac de barrage de Grand Coulee ou lac Franklin D. Roosevelt sur la Columbia River aux États-Unis, ont eu lieu des centaines de glissements causés par le réservoir depuis qu'a été rempli le lac peu après 1940. Ces glissements avaient lieu et ont encore lieu au milieu des matériaux non consolidés d'origine glacio-fluviale et d'âge Pléistocène, qui constituent en grande partie les bords du réservoir. Le Downie Slide au Canada donne encore un exemple provenant des environs de la Columbia River. Cet important glissement de rochers de l'époque préhistorique comprend 1500 millions de m^3 et va se situer aux bords d'un grand réservoir dont les plans et la construction sont encore en cours.

Aux États-Unis, on commence à donner plus d'importance aux programmes de sécurité en ce qui concerne des barrages, à la suite de l'effondrement du Teton Dam et du Toccoa Dam. Bien que ces effondrements ne résultassent pas des glissements de bord de réservoir, l'importance de la sécurité des barrages a excité l'intérêt national sur les glissements de terrain qui constituent des risques pour les réservoirs et leurs barrages.

Introduction

The existence of mass movements of reservoir slopes as a result of the reservoirs themselves has long been recognized as a problem in planning, design, construction, and maintenance of dams and reservoirs (Lane 1967). However, not until the well known 1963 Vaiont Reservoir Slide in Italy, did engineers and geologists fully realize the possible disastrous consequences of reservoir slope failures. Failures of reservoir slopes pose several types of problems related to the operation and safety of dams; examples are:

(1) generation of surges that may endanger lives and cause damage to the dam and/or developments along the reservoir shore;

(2) direct damage to the dam, outlet works, or other structures adjacent to the reservoir;

(3) reduced storage capacity; and

(4) delays in construction.

Mass movements of reservoir-rim slopes can occur as a result of either filling or drawdown of a reservoir. Filling a reservoir causes saturation of the earth mass composing the slope, with resultant reduction of shear strength related to increased pore pressures in the soil and rock. In addition, the water load in the reservoir may induce seismicity and perhaps even cause surface fault displacement, with possible triggering of landslides in nearby reservoir slopes. Sudden drawdown of a reservoir can threaten stability by removing lateral confining pressure of the reservoir on lower slopes of the reservoir rim while the earth mass still has reduced shear strength resulting from high pore-water and seepage pressures.

Types of slope movements of greatest danger to reservoirs

Slope movements can be classified by types of movement and geologic materials as shown in Fig. 1. Although almost all types of rock and soil slope movements can result from the filling or sudden drawdown of a reservoir, certain types generally result in the greatest financial loss and danger to the populace. In general, reservoir-related rock slides have been more destructive than slides in surficial materials because rock slides often are large and move at high velocity, thus creating large surges if they enter reservoirs. The best known example of a rock slide caused by a reservoir is, of course, the 1963 Vaiont Reservoir Slide which killed some 3,000 people in northern Italy (Kiersch 1964; Müller 1964).

Slope movements in rock

As shown in Fig. 1, rock slides can be divided into two main types: rotational and translational (Varnes 1978). The rotational rock slide (Fig. 2), which is also known as a rock slump, moves at an extremely

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
		MANY UNITS	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX			Combination of two or more principal types of movement		

Fig. 1: Classification of slope movements (from Varnes 1978).

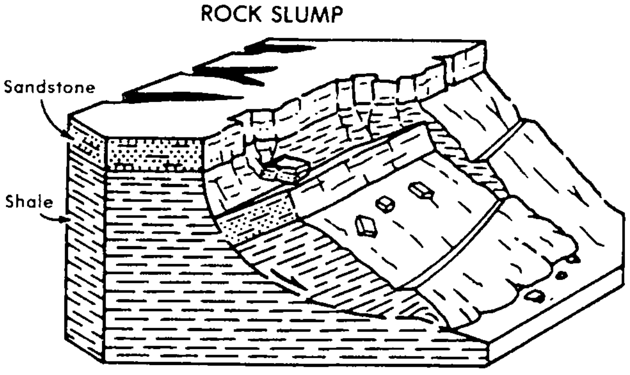

Fig. 2: Rock slump (from Varnes 1978). This type of rotational rock slide has extremely slow to moderate velocity.

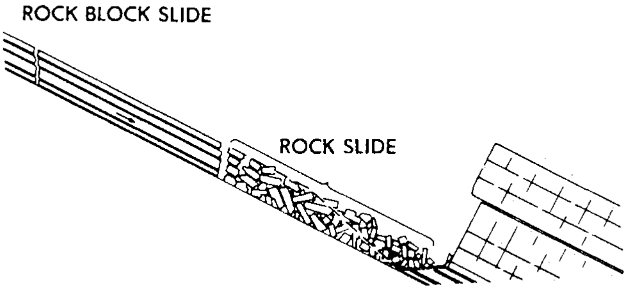

Fig. 3: Rock slide and rock block slide (from Varnes 1978). These slides often have large volumes and move at high velocities; upon entering reservoirs, they may cause surges of considerable magnitude.

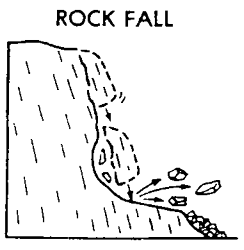

Fig. 4: Rock fall (from Varnes 1978). Exreme velocity can result in dangerous wave activity.

slow to moderate rate; thus while rotational rock slides may be large and have considerable effect on reservoir volume, they seldom cause large reservoir surges resulting in catastrophe such as that which occurred at Vaiont.

Translational rock slides or rock block slides (Fig. 3) move predominantly along structurally controlled surfaces or zones of weakness such as faults, joints, and bedding planes (Varnes 1978). They often move at high velocities and, upon entering a reservoir, may cause surges of large magnitude. In the Vaiont disaster, a huge wave caused by the slide submerged the far side of the reservoir to a height of over 250 m and passed over the dam to a height of approximately 100 m (Kiersch 1964). Another example of a huge wave caused by a rock slide entering a body of water at high velocity was the surge in Lituya Bay, Alaska, which occurred in July 1958. This wave occurred when approximately 30 million m^3 of rock plunged into Gilbert Inlet from a maximum altitude of over 900 m. This rock slide, which was earthquaketriggered, caused water to surge over the opposite wall of the inlet to a maximum altitude of 530 m and generated a gravity wave that moved out of the bay at a speed of as much as 210 km/hr (Miller 1960). Because the area was unpopulated, there were no shore facilities to be damaged; however, two fishermen drowned when their boat capsized in the bay. Although this giant wave occurred in a natural inlet rather than a reservoir, it is indicative of possible reservoir wave action under extreme conditions.

Although rock falls (Fig. 4) usually are not as large as rock slides, they occur at extremely high velocities, and thus are capable of damage to facilities or of generating fairly large waves. An example of a hazard due to possible rock fall exists at Lake Powell, the reservoir formed by Glen Canyon Dam along the border between Arizona and Utah (Brokaw 1974). The potential fall of large slabs of Wingate and Navajo Sandstones along the shore of Lake Powell poses a hazard to boaters and compers who utilize the reservoir for recreational purposes. Rock falls occur where the reservoir waters have removed or saturated the rocks supporting the sandstone slabs; the slabs then fail along near-vertical joints and fall into the water. The fall of a single slab 90 m long and 45 m high has been documented. The most dangerous aspect of such rock falls into Lake Powell or similar reservoirs is the large waves they produce, which increase in height as they surge into narrow side canyons.

Slope movements in surficial materials

Although landslides in surficial materials generally are smaller and move more slowly than certain types of rock slides, occasionally surficial movements can result in considerable damage; of particular interest are debris movements. Debris movements of the greatest potential hazard to reservoirs are debris slides (Fig. 5), debris flows (Fig. 6), and debris avalanches (a type of debris flow) (Fig. 7). All three of these movements are commonly at high velocity. Generally they are small enough to cause only local damage, but occasionally they may result in moderate surge activity in a reservoir. These types of failures have been noted by Jones et al (1961) in coarse glacial and terrace deposits along the shores of Franklin D. Roosevelt Lake (the reservoir for Grand Coulee Dam) in the State of Wahington.

Slope movements which occur in finer engineering soils and which may affect reservoirs are earth slumps, earth slides, earth spreads, and earth flows. Although some earth slumps (Fig. 8) are large, they generally move slowly; thus they mainly cause only local damage and do not result in reservoir surges. Earth slumps occur commonly along reservoir walls, often as a result of reservoir filling or sudden drawdown.

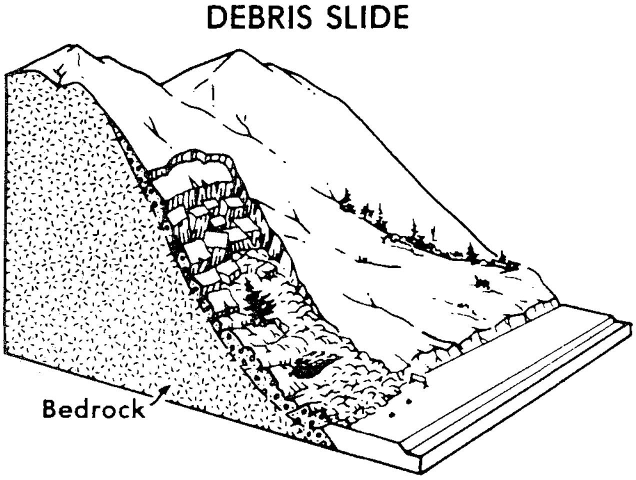

Fig. 5: Debris slide (from Varnes 1978). Movement can be very slow to rapid.

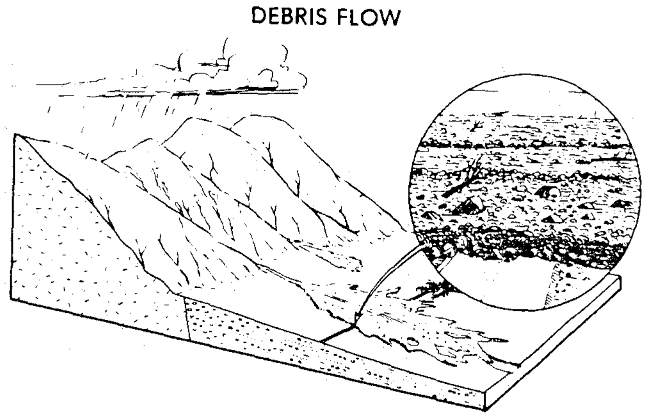

Fig. 6: Debris flow (from Varnes 1978). Movement generally is very rapid.

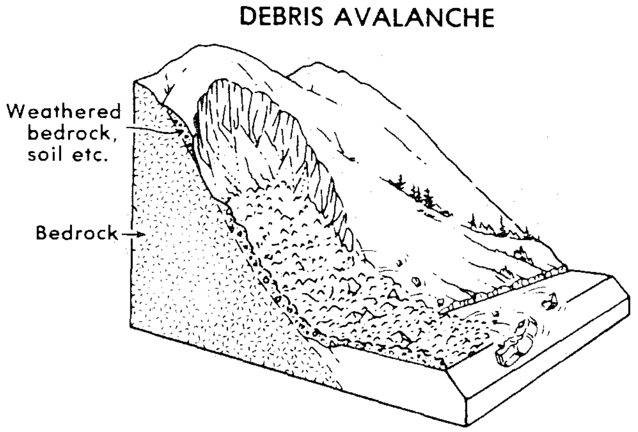

Fig. 7: Debris avalanche (from Varnes 1978). Movement is very rapid to extremely rapid.

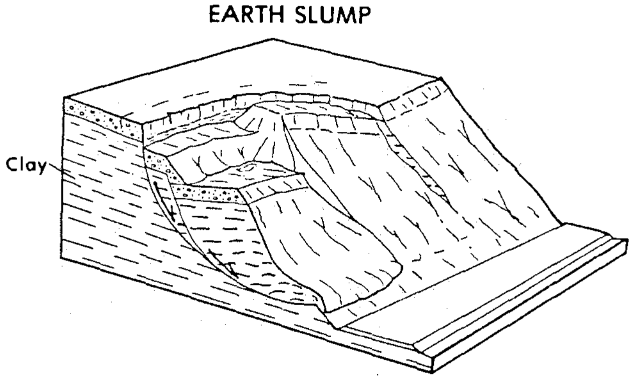

Fig. 8: Earth slump (from Varnes 1978). Although volume can be large, velocity generally is slow to moderate.

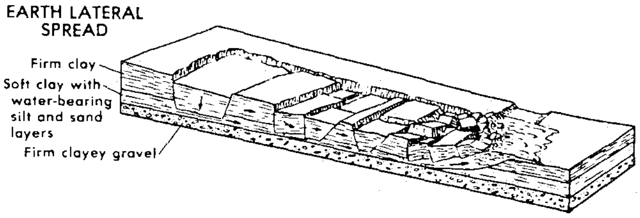

Fig. 9: Earth lateral spread (from Varnes 1978). Movement generally is very rapid.

Earth lateral spreads (Fig. 9) can occur where the reservoir rim is fairly flat and consists of alternating clay and water-bearing silt and sand layers. Although movement of spreads can be rapid, their volume is generally not great enough to result in large reservoir surges; thus damage from reservoir-induced lateral spreads is generally local.

The most common reservoir-induced earth flows are sand or silt flows (Fig. 10), which often occur during filling or sudden drawdown of a reservoir. Their velocities generally are rapid to very rapid, but the flows usually are not large enough to result in dangerous reservoir surges. Thus damage is most often limited to local areas in direct contact with the flows.

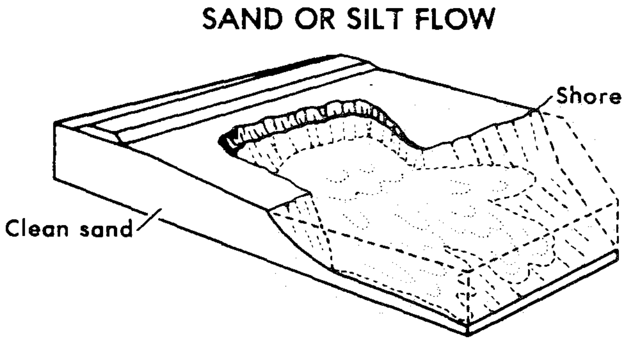

Fig. 10: Sand or silt flow (from Varnes 1978). Movement is generally rapid to very rapid.

Selected case studies in the United States and Canada

Although reservoir-induced landslides have occurred and will continue to occur in North America, the two current cases of paramount importance are on the Columbia River, one in the United States, the other in Canada. In the northeastern part of the State of Washington (see map, Fig. 11), the Grand Coulee Dam impoundment, Franklin D. Roosevelt Lake, has been the site of hundreds of reservoir-induced landslides since it was filled in the late 1930's and early 1940's. In British Columbia, Canada, the prehistoric Downie Slide north of Revelstoke (see Fig. 11) is of considerable importance because it forms part of the valley wall of the Columbia River at the intended site of a major reservoir which is still in the planning and

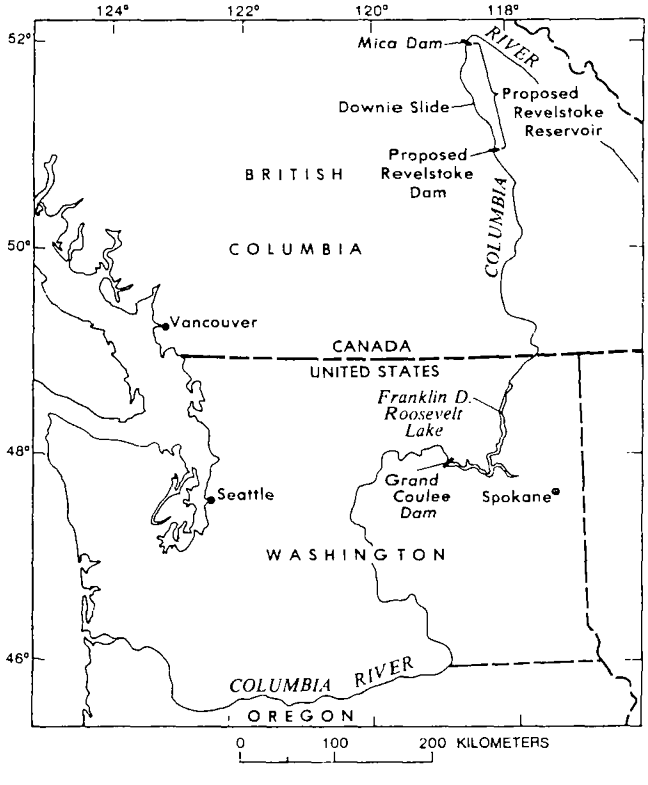

Fig. 11: Map of northwestern United States and southwestern Canada showing locations of Franklin D. Roosevelt Lake and the proposed Revelstoke Reservoir.

construction stage. Both of these cases contribute to the understanding of causes and mitigation of reservoir-induced landslides – Roosevelt Lake beause of its long history of landslides, and the Downie Slide as an example of the use of mitigative measures in the planning stage in order to prevent reactivation of an existing slide due to the impoundment of a major reservoir.

Landslides related to Franklin D. Roosevelt Lake

Construction of Grand Coulee Dam by the U. S. Bureau of Reclamation began in 1933. Roosevelt Lake slowly and intermittently was filled as construction proceeded until the dam was completed in 1942. The resulting reservoir created a lake 232 km long and raised the level of the Columbia River 107 m at the dam. Landslides occurred with great and unexpected frequency as Roosevelt Lake filled (Jones et al. 1961); in addition, many landslides have occurred since filling, particularly during periods of drawdown of the reservoir. These slides occurred, and are occuring, mainly in the relatively unconsolidated Pleistocene glaciofluvial deposits which compose much of the rim of the reservoir; thus they constitute landslide types fitting Varnes' categorization of landslides in engineering soils, such as earth slumps, earth spreads, earth flows, and debris flows. Although some individual landslides in these Pleistocene deposits have been large (see Fig. 12, 13, and 14) and the total volume of slope movement probably is about 50 – 100 million m^3, damages due to the slides have not been economically catastrophic and no deaths have resulted. This lack of catastrophe can be attributed to three causes: (1) individual slides in these Pleistocene soils have not been large enough, nor have they attained sufficient velocities, to produce large and far-reaching surges in the reservoir; (2) the area around the reservoir rim is only lightly-populated; (3) since the inception of the project, the Bureau of Reclamation has recognized the potential for landslides and has employed mitigative measures including restriction of development in areas with landslide potential.

Jones et al. (1961) studied some 500 landslides which occurred between 1941 and 1953 in the Pleistocene deposits bordering Roosevelt Lake. Fig. 15 presents the results of these studies in a histogram relating annual number of slide occurrences to filling and drawdown of the reservoir. Of the 500 slides recorded on this plot, 245, or 49 percent, occurred during the reservoir-filling period of 1941 – 1942, and 30 percent occurred during two periods of drawdown ranging from 10 – 20 m. Only minor slide activity occurred in other years. This strongly demonstrates the importance of both the rising reservoir and drawdown as causes of landslide activity.

Methodical records of landslides at Roosevelt Lake were not kept from 1954 through the mid-1960's. However, in the late 1960's the Bureau of Reclamation began a formal landslide surveillance program for a considerable portion of the shoreline of Roosevelt Lake. This was done in anticipation of increased landslide activity as a result of large drawdowns planned during construction of the forebay dam for the Grand Coulee Third Powerplant (U. S. Bureau of Reclamation 1968 – 1977). This program was limited to shoreline areas of greatest importance; thus only about 100 landslides were studied, compared to about 500 noted by Jones et al. in their earlier study of the entire shoreline.

As shown in Fig. 16, annual minimum pool levels for the past 10 years are about 20 – 25 m below the normal maximum pool, an annual drawdown considerably larger than occurred when the dam was first constructed; this larger drawdown is due to increased power demands in recent years. Added to the normal drawdown for this period were the special cases for 1969 and 1974 when the reservoir was drawn down approximately 40 m due to construction of the Third Powerplant. These drawdowns are all considerably larger than those that occurred during Jones' studies that led to the 1940's and 1950's data presented in Fig. 15. These large drawdowns are undoubtedly the primary cause of the increase in landslide activity from 1969 to 1975 depicted in Fig. 16; however, the activity of 1973 – 1975 probably was augmented by higher than average precipitation for those years.

Landslide activity apparently began to taper off in 1976 – 1977, some two to three years after the largest drawdown of Roosevelt Lake occurred. This decrease in landslide activity was probably a result of decreased precipitation rather than any effect of drawdown. It will be interesting to study the landslide data for 1978 and ensuing years to see if the reservoir rim continues the trend toward stability

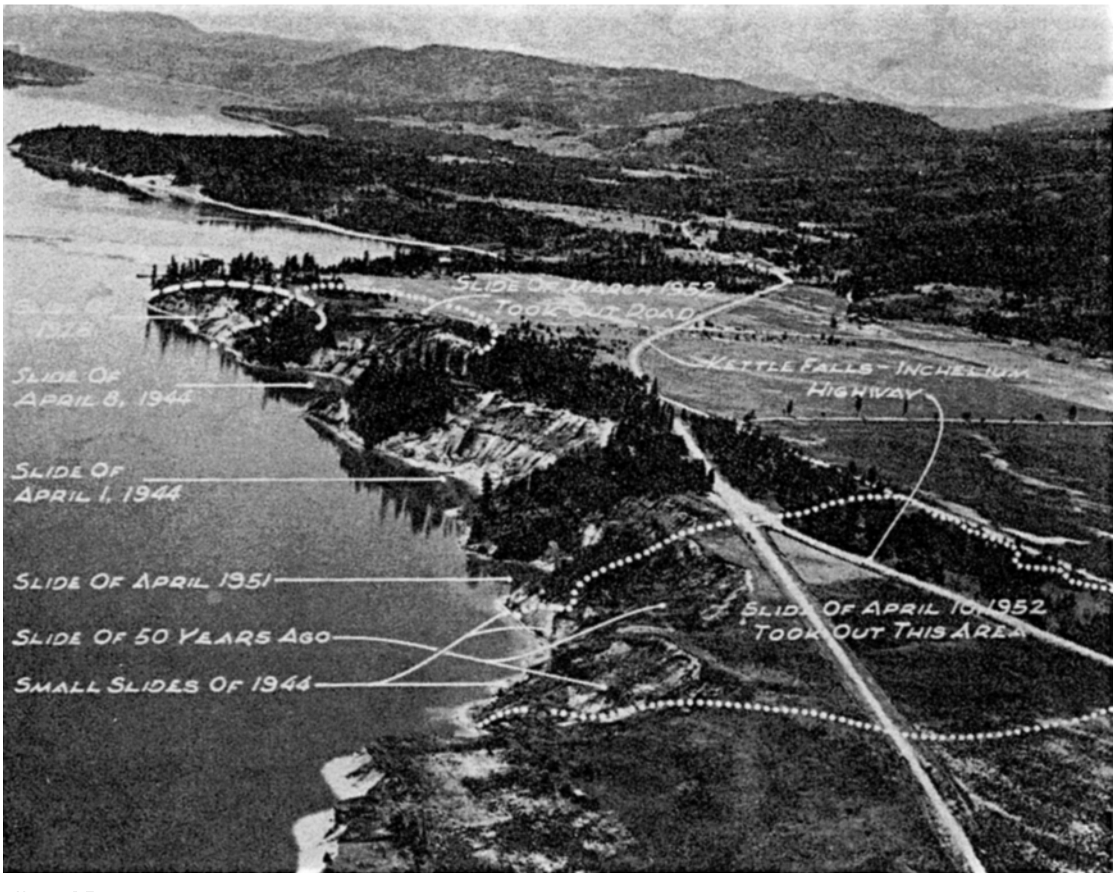

Fig. 12: Shoreline of Roosevelt Lake near Kettle Falls, Washington, May 1951 (from Jones et al. 1961; Varnes 1978). (Photograph by F. O. Jones, U. S. Geological Survey.)

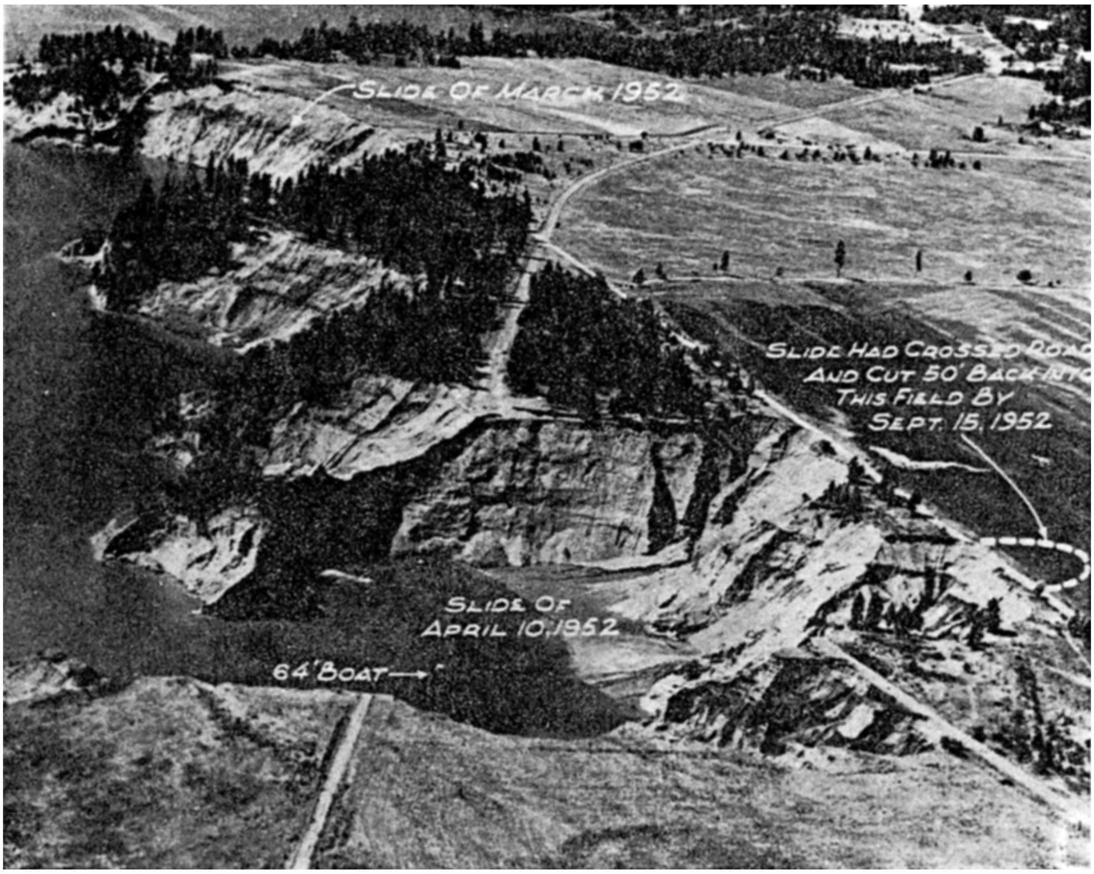

Fig. 13: Shoreline of Figure 12 as it looked on August 1, 1952. The landslide of April 10, 1952, involving about 11 million m³, took place by progressive slumping, liquefaction, and flowing of Pleistocene glaciofluvial sediments through a narrow opening (from Jones et al. 1961; Varnes 1978). (Photograph by F. O. Jones, U. S. Geological Survey.)

Fig. 14: Jackson Springs slide on the Spokane arm of Roosevelt Lake. This earth slump, which had a volume estimated at over 11 million m³, occurred on March 26, 1969, on a terrace consisting of alternating beds of lacustrine clay, silt, and sand. The slump occurred during a period of extreme drawdown necessitated by excavation for a forebay dam preliminary to construction of the Third Powerplant at Grand Coulee Dam (U. S. Bureau of Reclamation 1969).
(Photograph courtesy of U. S. Bureau of Reclamation.)

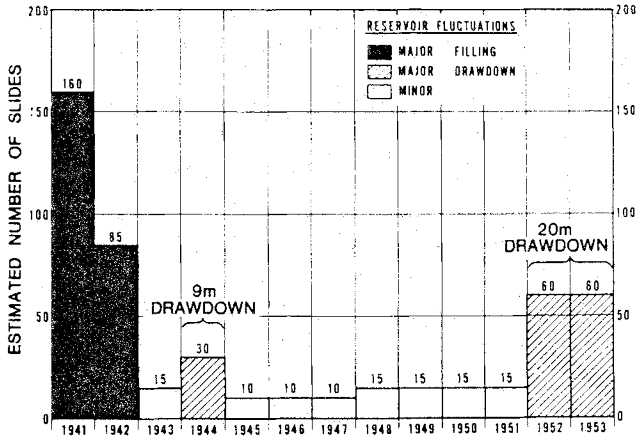

Fig. 15: Histogram showing estimated frequency of all landslides along shore of Franklin D. Roosevelt Lake, 1941 – 1953. Number of landslides during this period was approximately 500. (From Jones et al. 1961; Lane 1967.)

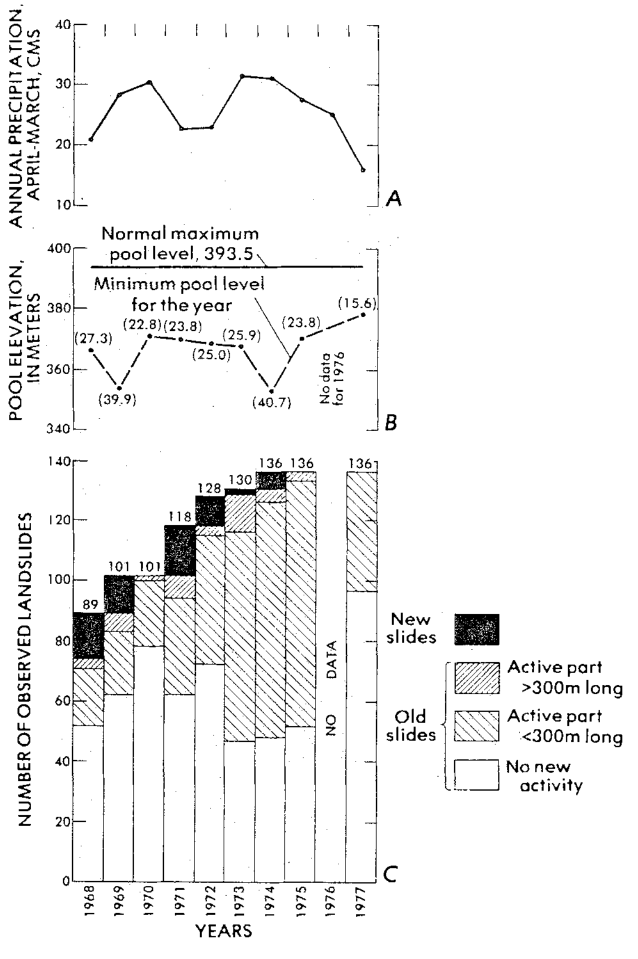

Fig. 16: Annual precipitation (A), pool elevations (B), and numbers of observed landslides for part of the shoreline of Roosevelt Lake (C), 1968 – 1977. Annual landslide observations were made in early April, which was usually the time of greatest drawdown and greatest landslide activity; thus precipitation records are for the preceding April to March as measured at Coulee Dam, Washington. Average annual precipitation for the 40-year period from 1938 – 1977 was 26.2 cm. Numbers in parentheses in (B) are maximum reservoir drawdowns in meters. Large drawdowns of 1969 and 1974 were a result of construction of the Third Powerplant for Grand Coulee Dam. (Original landslide and drawdown data from U. S. Bureau of Reclamation 1968 – 1977; precipitation data are from U. S. Department of Commerce 1938 – 1977.)

indicated in 1977. Although landslide activity for the rim of Roosevelt Lake probably will not commonly attain the levels of 1969 – 1975, the slopes have not reached equilibrium, and wet seasons combined with a continuing annual drawdown on the order of 20 m undoubtedly will result in continued landslide activity.

One of the best examples of sliding caused by the large drawdowns in this period was the Jackson Springs Slide (Fig. 14), which occurred during the period of extreme drawdown in 1969. An example of a large recent landslide that apparently was not related to these extreme drawdowns was the estimated 3 – 4 million m^3 reactivation of the Hughes Slide along the east bank of the San Poil arm of the reservoir in February 1978. This slide probably was caused by melting of 30 – 50 cm of snow, which resulted in saturation of the lacustrine silt, clay, and sand in the slide area.

In summary, the Pleistocene glaciofluvial deposits which form most of the shore of Roosevelt Lake have been subject to several hundred landslides since the reservoir began to be filled during construction of Grand Coulee Dam during the 1930's and early 1940's. The greatest percentage of landslide activity occurred during initial filling of the reservoir, but many slope failures also have been caused by intermittent drawdown of the reservoir level. In addition, occasional slope failures have occurred as natural phenomena, related more to wet winters than to fluctuation of the reservoir. Even though moderate annual drawdowns will be expected in the future because of heavy power demands, it should be expected that the amount of landslide activity will taper off and that, unless further extreme drawdowns occur, most new activity will consist of natural landslides.

The Downie Slide

As a result of investigations of alternative dam sites on the Columbia River north of Revelstoke, British Columbia, Canada, a large prehistoric rock slide on the west side of the river was discovered in 1956 (Piteau et al. 1978). This slide, which was subsequently named the Downie Slide for its location near the mouth of Downie Creek, has been included in this discussion because of its location on the proposed rim of a reservoir that is still in the planning and construction stage. As a case study it provides an excellent example of the use of geologic and geotechnical planning to prevent reactivation of a very large landslide, the toe of which will be partially inundated by a reservoir.

The Columbia River Valley north of Revelstoke is a glacially modified valley between the Selkirk Mountains to the east and the Monashee Mountains to the west. The river flows in a fairly wide channel in glaciofluvial deposits, except in the Downie Slide area where it becomes fast-flowing in a narrow canyon with rock walls. With a volume of approximately 1500 million m^3, the Downie Slide is one of the world's largest landslides. It is particularly important because of its relation to potential hydroelectric development of the Columbia River in the vicinity of Revelstoke. It is located approximately 66 km upstream from the Revelstoke Dam, which is now under construction, and 83 km downstream from Mica Dam (see Fig. 11). The toe of the Downie Slide extends in bedrock approximately 2500 m along the west bank of the Columbia River. It rises approximately 1000 m from river level to the bottom of a prominent 120-m-high scarp, some 3000 m back from the river. The slide mass, which has a maximum thickness of about 300 m, has moved an average distance of about 250 – 300 m toward the river (Gardner et al. 1976).

The rocks in the Downie Slide are assigned to the Shuswap Metamorphic Complex; they consist primarily of interbedded gneisses and mica schists (Gardner et al. 1976). The foliation of these metamorphic rocks dips to the east and northeast (that is, toward the river) at angles varying from about 15° – 30° (Piteau et al. 1978), with the average riverward dip in the slide mass being close to the average slope of the ground surface, 18° (Patton and Imrie 1977). There is the probability of a regional fault paralleling the river and hidden by gravel terraces. In addition, smaller faults have been mapped in the valley wall upstream from the slide.

The rocks of the Shuswap Metamorphic Complex are relatively competent except parallel to the foliation. Potentially unstable conditions occur when the foliation strikes parallel to a valley and dips at about the same angle as the valley wall. If the toe of a rock mass constituting such a valley wall is removed, the mass may become unstable and slide. At Downie, the toe support for the riverward-dipping rocks was probably removed by late Pleistocene glaciation and glacial meltwaters. At the same time, high groundwater levels probably reduced the shear strength of the rock mass (Gardner et al. 1976). This combination probably triggered major movement of the slide some 9,000 to 10,000 years ago. There is no evidence that high velocity movement has occurred at any time (Patton and Imrie 1977). At present the slide area is generally stable although parts of the slide show evidence of continuing local movement.

Under the terms of the Columbia River Treaty between Canada and the United States, the Revelstoke Hydroelectric Project, which is designed and owned by the British Columbia Hydro and Power Authority (B. C. Hydro), began to be constructed in March 1977. Revelstoke Dam, which is the main element of the Revelstoke Hydroelectric Project, is to be a 160-m-high concrete gravity dam connected to an earth-fill wing; total crest length will be about 1600 m. The dam site is located about 5 km north of Revelstoke. At full impoundment its reservoir will reach to the foot of Mica Dam, some 140 km upstream, and will submerge the lowest 60 m of the toe of Downie Slide.

During feasibility studies for the Revelstoke Project in 1971 – 1972, the stability of the Downie Slide was reviewed by geologists and engineers of B. C. Hydro, who concluded that no large-scale reactivation of the slide will take place due to submergence of its toe by the planned reservoir. However, because of the magnitude of the slide and the potential risk to the city of Revelstoke, immediately downstream from the dam, B. C. Hydro, at the commencement of the Revelstoke Project in 1973, engaged a panel of geotechnical experts to make an independent assessment of the effects of submerging the toe of the slide. The members of the Downie Slide Review Panel, W. I. Gardner, D. H. MacDonald, and F. D. Patton were to advise B. C. Hydro, in broad terms, on the following:

(1) existence and nature of a slide hazard under various development options for the Revelstoke Project,

(2) the possibility of success of practical remedial measures, and

(3) nature of anticipated flooding from possible renewal of slide activity (Patton and Imrie 1977).

After initial studies of the slide, the Review Panel recommended a program of exploratory investigation during the period 1973 – 1975; these studies included the drilling of 20 exploratory boreholes totaling approximately 4100 m, the driving of a 266-m-long, 2 x 2.5 m adit into the slide, geologic mapping, instrumentation, and monitoring. Based on these investigations and analyses of stability of the slide area, the Review Panel concluded that the stability could be increased by installation of a drainage system that would more than compensate for any decrease in strength of the slide mass due to submergence of the toe (Patton and Imrie 1977).

As a result of this conclusion by the Review Panel, B. C. Hydro is going ahead with project planning and construction. To facilitate drainage of the slide, some 1350 m of drainage adits have been constructed. In addition, an extensive ground-water and movement monitoring system is being installed. This system currently consists of 61 piezometers (installed in 19 drill holes to depths of as much as 365 m, 12 borehole inclinometers, and more than 40 surface survey monuments (F. D. Patton, oral commun. 1979).

Relation of current dam safety programs to the hazard of reservoir-induced landslides in the United States

Recent inventory data compiled by the U. S. Army Corps of Engineers show that, as of 1977, nearly 50,000 dams in the United States are 7.6 m or more in height or have a capacity of at least 62,000 m^3 (Federal Coordinating Council for Science, Engineering, and Technology 1977). As shown in Fig. 17, the number of new dams has been growing at a rate of about 1600 per year since 1960. Unless efforts are increased to avoid or prevent reservoir-induced landslides, this rapidly expanding number of dams will result in a greater number of such landslides. Interestingly, the failures of the Teton Dam, Idaho, in 1976 (U. S. Department of the Interior Teton Dam Failure Review Group 1977), and Toccoa Dam, Georgia, in 1977 (Federal Investigative Board 1977), which did not result from landslides of the reservoir rims, have drastically increased awareness of the importance of dam-safety measures in the United States and, thus, have had an indirect effect on interest in landslides that constitute hazards to reservoirs and dams.

Federal dams

As noted in Fig. 17, only about 2000 of the dams in the United States are classified as Federal dams, i. e., they are owned and operated by agencies of the Federal Government, such as the Corps of Engineers or the Bureau of Reclamation. However, these Federal dams constitute a high percentage of the large dams in the nation; their reservoirs also are large, and, in some cases, these reservoirs are subject to landslides. Thus the Federal dam-building agencies are well aware of the problems of landslides related to reservoirs and have taken actions to reduce the danger therefrom. The most formal program of study of such slides is the Bureau of Reclamation's "Landslide Surveillance Program", the essential features of which include landslide classification, an automatic data-processing program for computerized listing of landslides, and requirements for inspection, monitoring, and remedial measures (U. S. Bureau of Reclamation 1973). The purpose of the program is to register

> "all significant landslides or potential slide areas which have been or could be aggravated by the construction or operation of existing project facilities designed and constructed by the Bureau and all significant landslide areas which could endanger existing project facilities (or persons using them) for wich the Bureau has responsibility of examination for maintenance and safety purposes."

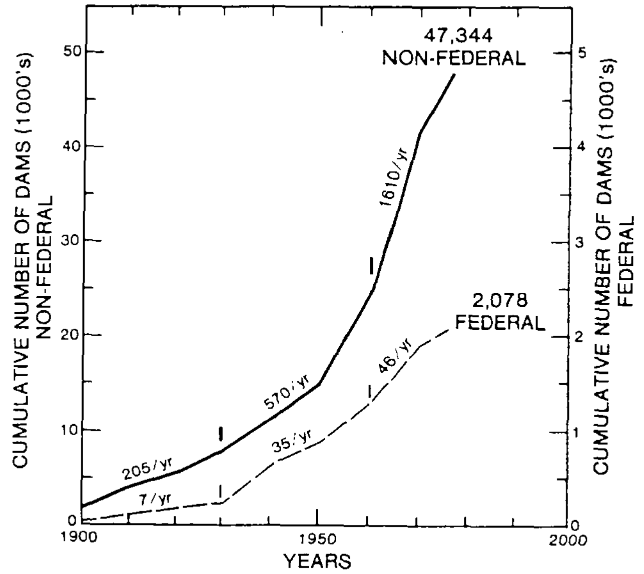

Fig. 17: U. S. growth rate trends for Federal and non-Federal dams, 1900 – 1977 (Federal Coordinating Council for Science, Engineering, and Technology 1977).

In its 1977 review of the Bureau of Reclamation's dam safety program, the National Research Council's Committee on the Safety of Dams recommended that the Bureau under its Landslide Surveillance Program should

> "(1) Complete the inventory by identifying all significant active, inactive and potential landslides at every reservoir and wherever the landscape may be affected by Bureau.
>
> (2) Establish the degree of risk present in each landslide.
>
> (3) Take the action necessary to mitigate risk situations.
>
> (4) Establish priorities for further instrumentation, geological investigations and analytical study where the risk of a landslide is high and where possible establish threshold values such as maximum credible earthquake, height of ground water, rate of drawdown, and lateral movement.
>
> (5) Establish contingency plans in the event of high-hazard slides" (National Research Council, Committee on the Safety of Dams 1977).

Other Federal dam-building agencies have not instituted formalized landslide study programs similar to that of the Bureau of Reclamation. However, each of these agencies is very aware of the landslide hazard and utilizes its own procedures for landslide surveillance. For example, the Corps of Engineers in its planning for future Federal dams conducts detailed reservoir-rim studies to note potential landslide hazards. In addition, for existing dams they monitor any potentially significant landslide areas under their periodic dam and reservoir inspection programs.

Non-Federal dams

As shown in Fig. 17, nearly 48,000 of the approximately 50,000 dams in the United States in 1977 were non-Federally owned dams, a great percentage of these being small dams. The Corps of Engineers has designated that 9000 of these non-Federal dams present high hazard to downstream life and property if failure should occur (U. S. Department of the Army 1978). On November 28, 1977, President Carter directed the Department of the Army to immediately begin inspecting these 9000 high-harzard non-Federal dams. These dams are being inspected according to the Army's Recommended Guidelines for Safety Inspection of Dams (U. S. Department of the Army 1976) which, in relation to stability of reservoir shorelines, specifically directs that "The landforms around the reservoir should be examined for indications of major active or inactive landslide areas and to determine susceptibility of bedrock stratigraphy to massive landslides of sufficient magnitude to significantly reduce reservoir capacity or create waves that might overtop the dam." During the first year of inspection, 1793 of the 9000 high-hazard dams were inspected and 354 were determined to be unsafe; however, the records indicate that none of these were threatened by landslides related to the reservoirs (U. S. Department of the Army 1978).

Conclusions

Failures in different parts of the world in recent years have focused increasing attention on safe functioning of dams and reservoirs. The catastrophic landslide into Vaiont Reservoir in 1963 dramatized the importance of landslide hazards to reservoirs; before that, landsliding had been considered a major threat mainly as related to dams and their associated structures. No comprehensive studies have been made of reservoir-induced landsliding throughout the United States, but the problem is a serious one which has resulted in large and continuing economic losses. For example, Jones et al. (1961) have noted that landslides along the shore of Lake Roosevelt behind Grand Coulee Dam in the State of Washington cost taxpayers and private property owners at least Dollar 20 million for avoidance and damage correction between 1934 and 1952; Jones' estimates did not include loss of storage and subsequent losses of hydroelectric capability.

Landslides that pose the most serious threat to the safe operation of a reservoir are large-volume, high-velocity types including rock slides, rock falls, debris flows, and debris avalanches. Where the threat of a major landslide can be identified before reservoir construction, it is possible to analyze the hazard and design remedial measures. For example, the Downie Slide on the Columbia River in Canada will be partially inundated by Revelstoke Reservoir. Early detection of the potential hazard permitted design of a drainage system that is intended to more than offset the negative effect of partial submergence of the toe of the landslide.

In the United States, the Federal agencies involved in building dams have either formal or informal programs of landslide surveillance for Federal reservoirs. In addition, the Corps of Engineers has been directed to inspect some 9000 non-Federal dams that present a high potential for loss of life and property if they should fail; the guidelines for these safety inspections include specific surveillance for existing or potential landslides.

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