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Debris flow affecting the Cubatão Oil Refinery, Brazil

Abstract On February 6, 1994, a large debris flow developed because of intense rains in a 800-m-high mountain range called Serra do Cubatão, the local name for the Serra do Mar, located along the coast of the state of São Paulo, Brazil. It affected the Presidente Bernardes Refinery, owned by Petrobrás, in Cubatão. The damages amounted to about US \$40 million because of the muck cleaning, repairs, and 3-week interruption of the operations. This prompted Petrobrás to conduct studies, carried out by the authors, to develop protection works, which were done at a cost of approximately US \$12 million. The paper describes the studies conducted on debris flow mechanics. A new criteria to define rainfall intensities that trigger debris flows is presented, as well as a correlation of slipped area with soil porosity and rain intensity. Also presented are (a) an actual grain size distribution of a deposited material, determined by laboratory and a large-scale field test, and (b) the size distribution of large boulders along the river bed. Based on theory, empirical experience and back-analysis of the events, the main parameters as the front velocity, the peak discharge and the volume of the transported sediments were determined in a rational basis for the design of the protection works. Finally, the paper describes the set of the protection works built, emphasizing their concept and function. They also included some low-cost innovative works.

Keywords Debris flow · Triggering conditions · Design parameters · Protection works

Introduction: general setting

The site

The Presidente Bernardes Refinery (RPBC), owned by Petrobras, is located at the base of a mountain range that extends for about 1,500 km along the southeast coast of Brazil, called Serra do Mar (Sea Sierra), spanning the states of Santa Catarina to Espírito Santo and running north–south the length of the state of São Paulo. This mountain range is generally about 750 to 800 m high but reaches 2,000 m locally. The debris flow in question occurred in a stretch locally called Serra do Cubatão. A satellite image (Fig. 1) shows its proximity to the sea and, nearby, the city of São Paulo.

The region is of great importance, as it links, by highway and railroad, the industrial areas of the city of São Paulo and other cities in the state to the port of Santos. In the lowlands of the Cubatão region, a complex of heavy and transformation industries is situated. For this reason, landslides and debris flows in the area cause great impacts to industries and to the infrastructure.

The geological conditions

The Serra do Mar mountain range is composed of Pre-Cambrian metamorphic rocks, consisting of gneisses, granitic gneisses, and some subsidiary mica-schists, calcareous rocks, etc. The schistosity and banding of the gneiss is generally parallel to the mountain

range, about 60°N–70°E, with steep dips to both the SE and NW. The hills are steep, averaging 35°, but locally, they can reach 45° or more at the higher elevations and decline to less than 20° at the base of the hills. These more gentle slopes are comprised of colluvium and talus deposits overlaying bedrock and residual soils.

The linearity of the range is believed to be a result of tension in this part of the earth's crust after the continental drift. Several normal faults were formed in the land and offshore, with blocks subsidence. One example is the Paraíba River valley, a linear depression separating two mountain ranges, considered to be a rift valley formed by a series of normal faults (Almeida and Carneiro 1998).

The climate is tropical with hot and humid weather. As a consequence, the weathering of the rocks is intense. Upslope from the colluvium and talus depositions, there is a thick mantle of residual soil, with progressive grading to saprolite and altered rock, reaching up to 60 m in depth in some locations. In the upper part of the mountain range, because of the higher inclination, the soil cover is generally thinner because of landslides.

In rainy periods, the colluvium is unstable and affects highways and other engineering works. They have the same constitution as the gneissic residual soils, a mixture of clayey and sandy soils with boulders and rock fragments in different weathering stages and are very heterogeneous. The first technical reference to the stability of colluvium and talus in the area was made by Terzaghi (1947) for the Cubatão Power Plant in construction at that time.

Below elevation of 12 m above sea level, the substratum is composed of recent marine deposits, comprised of thin sand layers and soft black organic clay up to 50 m thick. This coastal area is typically a marshland.

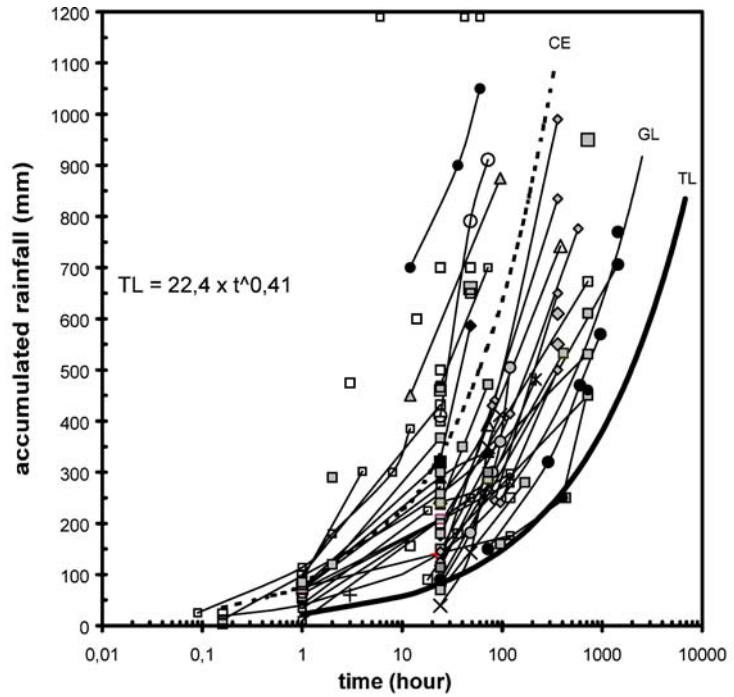
Rainfall and debris flow occurrences in the region

The annual rainfall in the Serra do Cubatão is about 3,000 mm but may occasionally reach 4,500 mm. The temperature generally ranges from 17 to 36°C over the year. Rains are usually caused by cold fronts coming from the south (Argentine–Chilean Andes), as shown in Fig. 2. An enhancement of the rain intensity may occur by orographic effect because of the mountain range.

Intense rains in the recent past caused numerous slides and debris flow in different parts of the Serra do Mar in the state of São Paulo and the neighboring state of Rio de Janeiro to the north. The disasters of Serra das Araras (1967), Grota Funda (1975), at Cubatão (1985 and 1988), and others were reported in an inventory of debris flows in Brazil by Gramani and Kanji (2001). Some drastic examples are shown by the aerial photographs after intense rains in 1967 at the Serra de Caraguatubá and in 1985 at the Serra do Cubatão, depicted in Figs. 3 and 4, respectively.

In the Serra do Cubatão, in less than 10 km of the mountain range, eight debris flow events were observed between 1971 and 1996, affecting some of the industries located close to the base of the hill slopes. To study the triggering rains at the region, the rains that caused these events were obtained, as summarized in Table 1.

Fig. 1 Satellite image of a portion of the Serra do Mar mountain range



- Colombia (some cases)
 - + Antofagasta91(CHILE)
 - ▲ SAraras67(BR)
 - ◇ RJaneiro88(BR)¹
 - △ Ubatuba96(BR)
 - × MtQuieto00(BR)
 - Outros (National Cases)
 - Critical Curve-Triggering Limit (TL)
 - - - Limit Curve of Catastrophic Events (CE)
 - Maiquetia99(VEN)
 - ◆ Caragua67(BR)
 - △ Tubarao74(BR)
 - Cubatao94(BR)
 - * Via Anchieta99(BR)
 - CJordao00(BR)
 - Outros (Internacional Cases)
 - Limit Curve of Generalized Landslides (GL)
- 1 = multiples stations

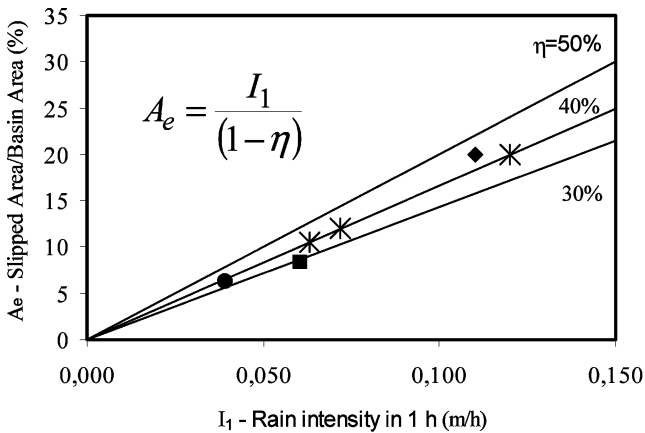
A correlation between accumulated rainfall (millimeter) and time (hours) and its severity related to landslides and debris flows from Serra do Mar and abroad was developed by Kanji et al. (1997, 2003), shown in Fig. 5. The TL line represents the triggering conditions for landslide occurrence, which is in accordance with other existing criteria (e.g., Tatizana et al. 1987; Ikeya 1989;

Capecchi and Focardi, 1988; Mozer and Hohersin 1983 in Guadagno 1991). The GL line represents the conditions above which landslides are generalized in the area and debris flows are possible. Finally, the CE line means catastrophic events, above which debris flows always occur.

Another correlation between the ratio (A_e) of total slipped area and the basin area was developed by Massad (2002) based on several Brazilian cases. In its general form, it may be written as:

$$A_e = \frac{c}{(1-c)} \cdot \frac{I_1}{e} \cdot \frac{(1-p)}{(1-\eta)} \quad (1a)$$

where c is the solid concentration per unit volume; I_1 , the amount of rain (meters per hour) in the hour that precede the debris flow;



- ◆ Timbé do Sul
- Rio Cachoeira/Braço Norte
- * Caraguatatuba
- Córrego das Pedras (RPBC)

Fig. 2 Image of weather satellite of southern Brazil, with cloudy cold front over the states of São Paulo and Rio de Janeiro

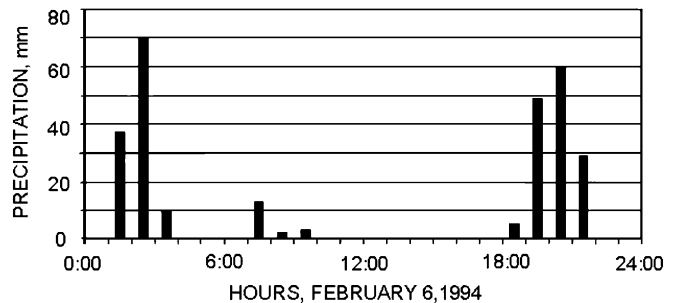


Fig. 3 Landslide scars caused by intense rains at Caraguratatuba 1967

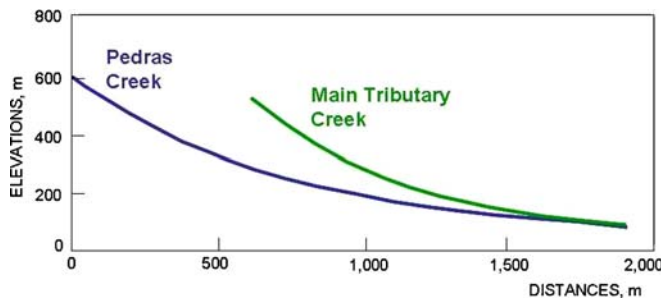


Fig. 4 Landslide scars at Serra do Cubatão 1985 (Wolle 1995)

e , the mean depth of the slip surfaces (meter); p , the volume of torrent bed and bank deposits as a percentage of total volume of solids; and η , the porosity of natural soil. For the Brazilian cases, $c=50\%$, $e \cong 1m$ (Wolle 1988), and p may be disregarded, as a first approximation, as negligible, and Eq. 1a could be simplified to:

$$A_e = \frac{I_1}{(1 - \eta)} \quad (1b)$$

The solid lines corresponding to different soil porosities according to the expression 1b are shown in Fig. 6.

The debris flows of February 6, 1994 at the Petrobras Refinery

The debris flow of February 6, 1994 (see Table 1) occurred on the hill slopes of the Serra do Cubatão, along the three hydrographic basins facing the refinery. The debris flow that occurred in the north basin was the largest and most important, and developed along the Pedras stream and the main tributary stream.

This event occurred at approximately 9:00 P.M. and was triggered by a rain with an intensity of 60 mm in 1 h, within a total rainfall of about 140 mm in 3 h. In the early morning of February 6, rain of 105 mm in 2 h, with 70 mm in 1 h was recorded. The rainfall record for the a 24-h period on February 6 is shown in Fig. 7. The rains for this event, when plotted in Fig. 5, border the CE line. The return time of the rains is calculated as being about 200 years.

The debris flows caused the destruction or damage of several facilities of the refinery, including a lateral protection dike at the base of the slope, destruction of fire water pipes, complete silting with mud and large stones of a large water reservoir, and inundation with water and mud of several tanking areas and of the industrial plant. As a consequence, plant operations were interrupted for about 3 weeks. The total loss amounts to about US \$40 million.

Some views are presented in Figs. 8 and 9. Fortunately, no human victims were reported, only the disappearance of some six

sheep grazing the vegetation of the riverbanks (surprisingly, they were not aware of the flow). Eight gabion dams about 4 to 5 m high, built along the Pedras stream after the 1985 event, were completely destroyed. The volume of debris removed was estimated to be about 300,000 m³ of debris (boulders, gravel, sand and mud, and logs).

Before the debris flows, the creeks were only 2 to 3 m wide and hardly visible because of the vegetation. After the debris flows, they suffered heavy erosion, enlarging to about 30 m and up to 40 m in some places. Air photos taken before and 1 month after the event (Figs. 10 and 11) show the dramatic changes. Figure 12 shows the erosion along both creeks and the initial deposits at the foot of the slopes after the February 6, 1994 event.

Although the main tributary stream is shorter than Pedras stream, it is steeper and erosion was more intense. Figure 13 illustrates the longitudinal profile of these creeks.

Removal of the deposited material exposed a horizon of boulders 3 m below the surface from previous debris flows that occurred in the basin. Similarly, in Caraguatutuba, after the catastrophic event of 1967, excavations of the deposits of the 1967 event discovered five additional layers of debris flow deposits. The wood from each buried deposit was carbon-14 dated, and the oldest event was about 3,000 years ago (Fulfaró et al. 1976). These facts show the periodical recurrence of the events.

The grain-size distribution of the deposits at the foot of the scarp in Cubatão was determined on a 5-m³ field sample from the 1996 debris flow deposit. The larger blocks were measured manually; size analysis of the finer portion was determined in the laboratory. The curve is shown in Fig. 14 (Massad et al. 2000). Note that the clay fraction is less than 5% of the deposit.

In the steeper upstream part of the channel, there are huge boulders that were transported by the torrent. A correlation of boulder size with riverbed inclination is shown in Fig. 15, along with observations of other similar events. A view of the deposits along the lower portion of the main tributary stream is shown in Fig. 16. From several lobes with frontal accumulation of larger boulders observed in the deposits along the creeks, it was clear that several pulses had occurred during the debris flow (see Fig. 17).

Table 2 summarizes the results of the air photo interpretation of the landslides at the North Basin, sorted by elevation. Note that the slope failures in the upper part of the basin are much longer than they are wide and that about 19% of the total area of that part of the basin failed. The volume corresponding to the total slipped area and river bank erosion was calculated to be about 226,000 m².

Design parameters for control works

As a consequence of the 1994 debris flow, the refinery owner decided to implement effective protection against future debris flows in the

Table 1 Major debris flows in Serra do Cubatão (Massad et al. 2000)

Place	Date	Stream or river	Total basin area (km ²)	Max rain, 1 h (mm)	Max rain, 24 h (mm)
Copebras	28th Jan 1976	Cachoeira Stream	4.00	39	276
		Braço Norte Stream	1.60		
RPBC and Perequê Basin	22–24th Jan 1985	Perequê River	11.40	84	265
		Pedras Stream	2.64		
Pedras Basin–Eletropaulo	20–22nd Jan 1988	Pedras River	3.40	25	135
Petrobras Refinery (RPBC)	6th Feb 1994	Pedras Stream	2.64	60	214
	9th Mar 1996	Main tributary-Pedras Stream	0.80	18	-

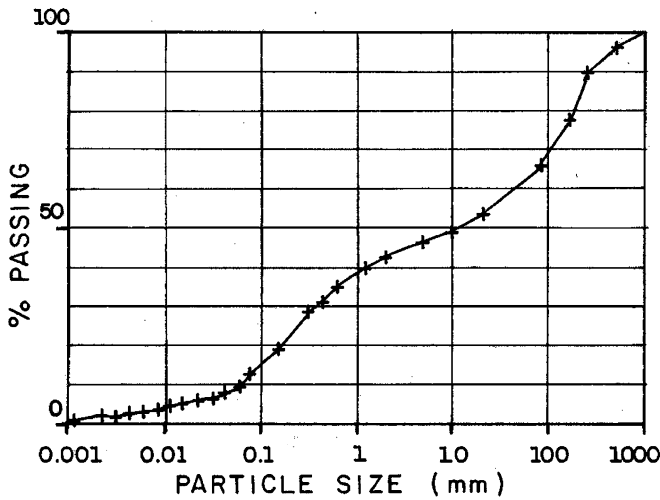


Fig. 5 Correlation between accumulated rain fall (millimeter) and time (hour) related to landslides and debris flows

same area. A multidisciplinary working group was formed to study the problem, understand the mechanism of debris flows, establish design criteria, and propose the required control works.

Initially, it was necessary to establish design parameters related mainly to the following aspects:

1. The velocities
2. The hydrographs and “debrisgraphs”
3. The debris flow peak discharge
4. The concentration of solids
5. The volume of sediments (solids) transported by the debris flow

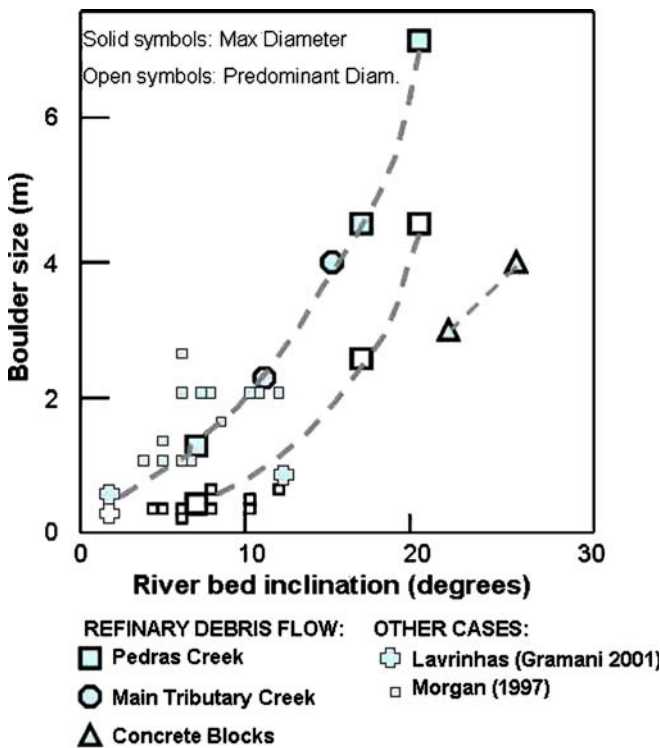


Fig. 6 Correlation between rain intensity in 1 h and slipped area for $c=50\%$, $e=1$ m, and $p=0$ (Massad 2002)

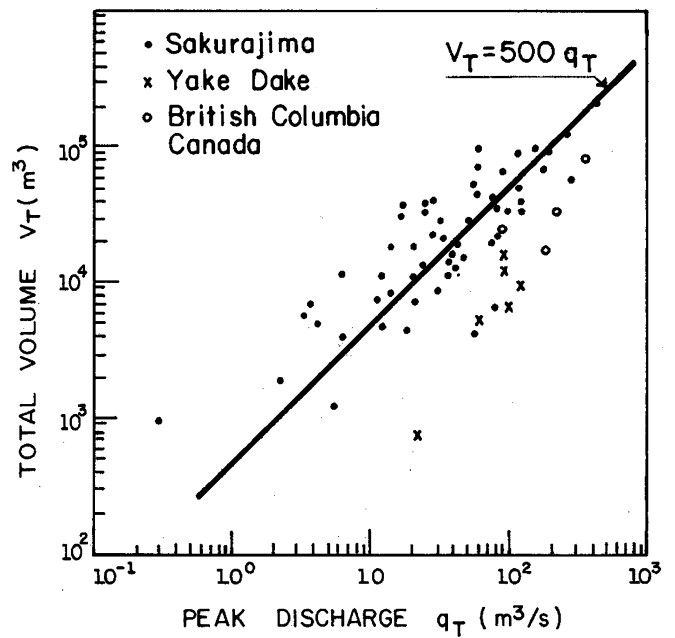


Fig. 7 Precipitation in the Pedras Stream Basin—debris flow started at 9:00 P.M., 6th Feb. 1994

In addition, it became very important to clearly define:

- (a) Shape of the hydraulic basin, whether spread with small affluents, bringing water and sediments to the main river, or mostly straight and concentrated in one main river
- (b) Inclination, and total length and height
- (c) Rain regime and the frequency of highly concentrated rain peaks
- (d) History of the site and the register of past debris flows
- (e) Nature of slopes, vegetation, thickness of soil, boulder concentration, unstable rock slopes, etc.
- (f) Local climate

Any use of formula from the literature must be adjusted to the local conditions and, whenever possible, cross-checked by different approaches. A more detailed discussion of the theme is presented by Massad et al. (1997).

The formulas used for the design of control works are mentioned below.

Flow velocity

The velocity can be computed by Rickenmann’s (1991) formula as:

$$v = 1.3 \cdot \text{sen}^{0.2}(\theta) \cdot q_o^{0.6} \cdot \frac{g^{0.2}}{d_{50}^{0.4}} \tag{2}$$

where θ is the slope inclination (degrees); g , the acceleration of gravity; d_{50} , the average grain size; and q_o , the specific discharge flow, given by:

$$q_o = \frac{Q_o}{b} \tag{3}$$

where b is the channel width, and Q_o is the 100 year estimated water discharge for the basin. This formula has yielded reasonable values in back analysis of the debris flows.

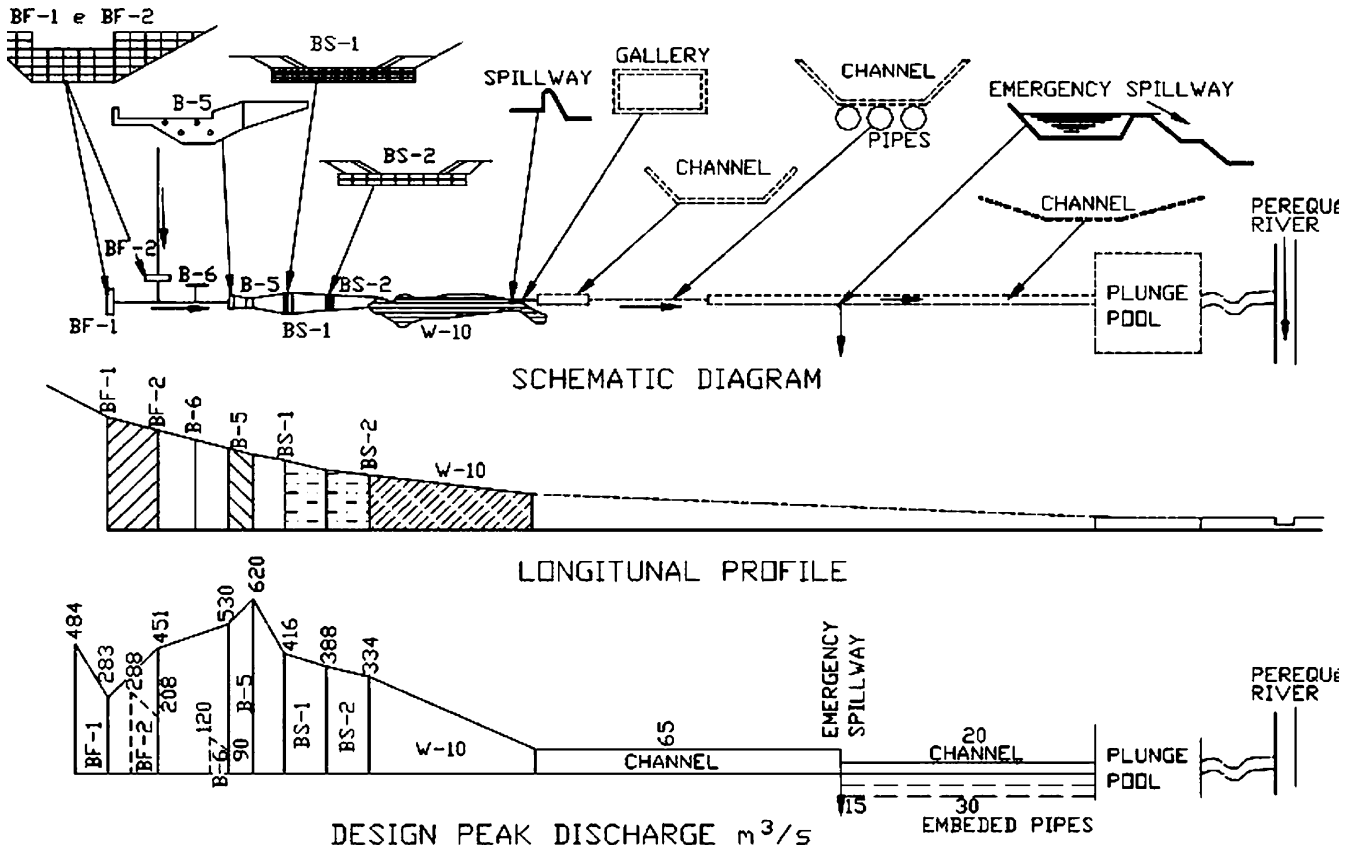


Fig. 8 Inundation of the industrial area

The hydrograph and the “debrisgraph”

“Debrisgraphs” can be drawn using the rain intensity, contribution area, runoff coefficient, and average slope of the basin. With respect to a normal hydrograph, the peak discharge of the debris flow can be 10 to 20 times larger, within a time interval 1/30 to 1/60 times smaller.

To the authors’ knowledge, there are no mathematical formulae to build a “debrisgraph” because it may vary quite significantly from site to site. Factors such as size of the basin, average slope, “river” course, vegetation, nature of rain, climate, and antropoc occupation of the area affect the shape and magnitude of “debrisgraphs.” Some mathematical models have been developed

(see, for instance, Takahashi 1991), but the input data required may be so difficult to get that the results may be questionable.

The peak discharge

The debris flow peak discharge (q_T) may be obtained by means of Takahashi’s (1991) equation:

$$q_T = \frac{c^*}{c^* - c} \cdot Q_0 \quad (4)$$



Fig. 9 Invasion of tanking areas and destruction of fire water pipes



Fig. 10 Aerial view of the region before the 1994 debris flows



Fig. 11 Aerial view of the region after the 1994 debris flows

where Q_0 is the flood water discharge and c and c^* are the solid concentrations per unit volume of the debris flow and the channel deposits. Because of the difficulties in estimating c^* , Eq. 4 loses accuracy. Therefore, empirical correlations are used to estimate V_s (or V_T) and q_T .

To figure the debris flow peak discharge (q_T), it is possible to apply an empirical correlation with the total volume (V_T), as is illustrated in Fig. 18 (Takahashi 1991). The data in this figure were obtained from Japan (Sakurajima Vulcano and Yake Dake) and Canada (British Columbia). The scatter is relatively large because of the influence of factors such as the hydrographic basin shape, channel conditions, and other flow characteristics (Takahashi 1991).

Nevertheless, the following equation was established:

$$V_T = 500 \cdot q_T \quad (5)$$

to be used in comparison with other methods. Note that the graph of Fig. 18 is bilogarithmic.

Araya Moya (1994) proposed an empirical formula to estimate the peak discharge of a debris flow based on his experience with Chilean debris flows:

$$q_T = 1.4 \cdot \frac{1}{(1-c)} \cdot 0.85 \cdot A \cdot I \cdot \frac{H^{0.19}}{L^{0.58}} \quad (6)$$

where c is the solid concentration in volume; A , the basin area in kilometer squared; I , the maximum average intensity of rain in



Fig. 12 Enlarging of the river beds to about 30 m and up to 40 m in some sites because of heavy erosion



Fig. 13 Longitudinal profile of the creeks at the North basin

24 h; H , the maximum difference in height within the basin; and L , the total length of the “river.”

In practical uses of Eq. 6 in the Cubatão region and based on back analysis of some Japanese and Brazilian debris flows, Massad et al. (1997) suggest replacing I with I_1 , i.e., the amount of rain that occurs during the 60 min that precede the debris-flows, which proved to be an accurate reflection of back-analyzed events.

Based on Eq. 5, a simpler expression was proposed by Massad et al. (1997):

$$q_T = \frac{2}{(1-c)} \cdot A \cdot I_1 \quad (7)$$

where A is the basin area in kilometer squared and I_1 the rainfall intensity accumulated in the hour that precedes the debris flow in millimeters per hour.



Fig. 14 Grain size distribution—1996 debris flow



Fig. 15 Boulder sizes for the 1996 debris flow as a function of riverbed inclination

Concentration of solids

The parameter c , the solid concentration in volume, can be computed by the formula (Takahashi 1991):

$$c = \gamma_o \cdot \frac{\text{tg}(\theta)}{(\delta - \gamma_o) \cdot [\text{tg}(\phi) - \text{tg}(\theta)]} \quad (8)$$

where γ_o is the density of the mud (water plus fines); δ , the specific gravity of the solid grains; ϕ , the friction angle of the granular material; and θ , the average slope.

The same formula can be rearranged to define the critical angle θ or the average slope angle, in which a debris flow will occur for particular values of γ_o and ϕ .

The volume of sediments (solids) transported by the debris-flow

The total volume of solids transported by a debris flow may be estimated on the basis of probable sediment runoff. Basically, there are three sources of material: (a) the soils from the slopes (sediment yield from landslides), (b) the torrent bed deposits, and (c) the deposits from torrent banks.

Experience in Japan (IPT 1990) indicates the following relationship between V_s (volume of solids) and A (basin area):

$$\frac{V_s}{A} = 30,000 \text{ to } 85,000 \text{ m}^3/\text{km}^2 \quad (9)$$

For the Cubatão north basin debris flow, this empirical formula results, on average, to approximately $152,000 \text{ m}^3$.

Another way to compute the volume of solids (V_s) is the evaluation of the amount of sediment runoff. In fact, an estimation was carried out for the entire North basin, including its tributaries, based on aerial photo (see Table 2) that were taken before and after the 1994 debris flow (Figs. 18 and 19).

Considering that the amount of granular material remobilized from the torrent bed deposits is about $40,000 \text{ m}^3$, this calculation led to a total volume of solids estimation as follows:

$$V_s = 226,000 \cdot (1 - 0.36) \cdot 0.85 + 40,000 \cong 163,000 \text{ m}^3 \quad (10)$$

A third way to estimate V_s is to use Eq. 5 combined with the following expression:

$$V_s = c \cdot V_T \quad (11)$$



Fig. 16 View of the deposits at the lower portion of the main tributary creek

derived from the concept of c , the solid concentration in volume, which leads to:

$$V_s = 500 \cdot c \cdot q_T \quad (12)$$

where q_T is given by Eqs. 6 or 7. Using the values of q_T shown in Table 3, we get $V_s = 158,000$ and $195,000 \text{ m}^3$ or, on average, $176,000 \text{ m}^3$.

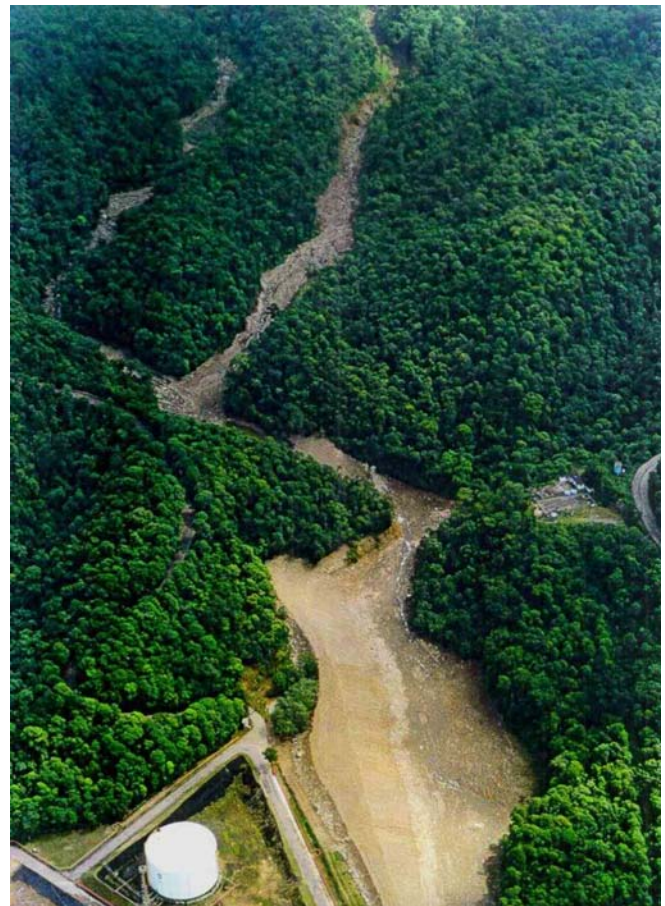


Fig. 17 View of lobes at the debris flow deposits

Table 2 Aerial photo interpretation of slope failures. Feb/1994, RPBC (Massad et al. 2000)

Elevation (m)	Slope (°)	Mean slipped area (m ²)	L/B	Number of slides	Total slipped area (m ²)	Basin area (km ²)	Slipped area in percent of basin area (%)
500–750	37	3,409	3	44 (45%)	150,000 (66%)	0.80	18.8
300–500	30	1,675	2	37 (38%)	62,000 (28%)	0.92	6.7
70–300	12	875	1	16 (17%)	14,000 (6%)	0.92	1.5
Total				97 (100%)	226,000 (100%)	2.64	8.6

L Landslide length and B its width

This figure and those given by Eqs. 9 and 10 are in a rough agreement with the measured value presented in Table 3 that includes two other cases of the Serra do Cubatão: Cachoeira and Braço Norte Streams.

From the previous considerations, the following parameters were defined for the design of the control works at the Cubatão Refinery:

1. Peak discharge flow, 700 m³/s
2. Total volume, 350,000 m³
3. Total volume of sediments, 175,000 m³ ($c=0.50$)
4. Intensity of rain, 10 mm/10 min
5. Velocity, 10 m/s

Control works

Basic principles

There appear to be some basic principles commonly used in engineering works for debris flow control that can be used in the design of such works. Heumader (2000), Mizuyama and Ishihara (1988), Ikeya (1976, 1989), and Cruz et al. (2000), among other authors, have described engineering works and “sabo” works (according to the Japanese designation) for debris flow control. These works have different purposes and should be designed to perform their role within an overall countermeasure plan that, whenever possible, should cover a significant part of the area subjected to such phenomena. They usually include:

1. Protection of the natural slopes to avoid slope failures, whenever feasible
2. Protection of the river banks against erosion
3. Reduction of river bed and margin erosion during a debris flow



Fig. 18 Peak discharge and total volume of debris flows (Takahashi 1991)

4. Breaking the energy of debris flow
5. Reduction of the peak discharge
6. Retention by dams of large rock blocks, boulders, and the granular material
7. Retention of trees, tree branches, and leaves transported by a debris flow;
8. Accumulation reservoirs to retain fine sediments
9. Removal of these sediments after a debris flow
10. Diverting and deflecting works to protect cultivated, inhabited, or erodable areas
11. Channeling of the water with suspended sediments to a nearby stream, river, or even the sea

Main works executed at the refinery area

Based on these general concepts, several different types of works were conceived for the North basin at Cubatão refinery. Figure 19

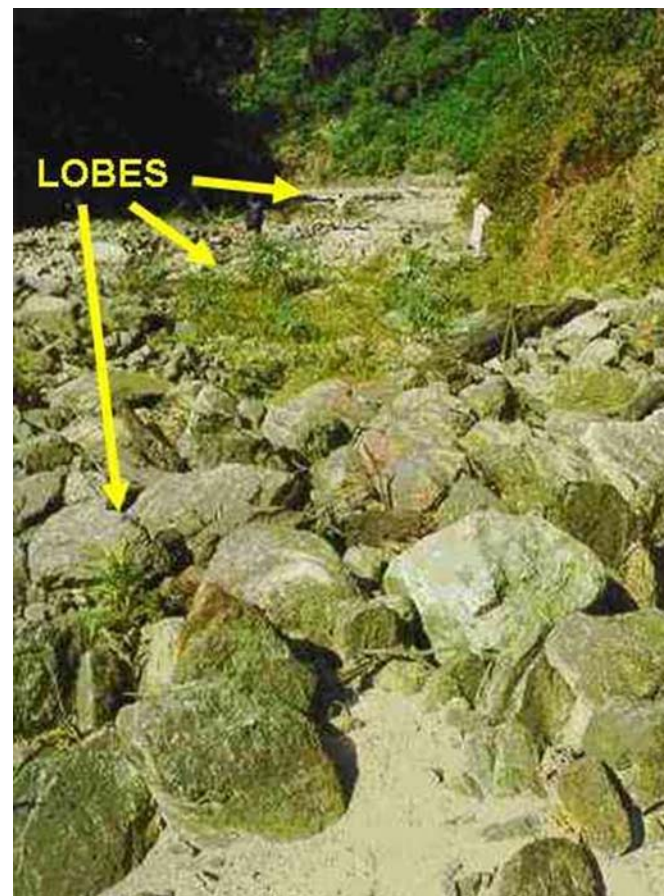


Fig. 19 Proposed sequence of works for the north basin

Table 3 Estimation of volume of solids for some cases in the Cubatão area

Debris flow	A (km ²)	H (m)	L (km)	I ₁ (mm/h)	q _T (m ³ /s), Eq. 6	q _T (m ³ /s), Eq. 7	V _s (m ³), Eqs. 7 and 12	V _s (m ³) measured
Cachoeira Stream (28/Jan./76), Copebras	4.00	596	3.8	39	580	620	156,000	–
Braço Norte Stream (28/Jan./76), Copebras	1.60	314	3.0	39	230	250	62,000	–
Pedras Stream (06/Feb./94), RPBC	2.64	650	2.4	60	780(<13)	630(<10)	158,000	150,000
Main tributary of Pedras Stream (9/Mar./96), RPBC	0.80	650	1.6	18*	90(22)	60(15)	14,000	16,000

Asterisk Adopted value, A basin area, H maximum difference in height within the basin, L total length of torrent, c solid concentration per unit volume (50% adopted), I₁ amount of rain in the hour that preceded the debris flow, (N) numbers inside parenthesis that mean q_T/Q₀

represents the linear arrangement of the protection works and the progressive reduction of the peak discharge. An important restraint was given by the capacity of spillway of the W-10 reservoir, limited to 65 m³/s. Therefore, the proposed sequence of works had the main purpose of breaking energy and to decrease gradually the peak discharge from 700 to 65 m³/s, as well as retain, as much as possible, the volume of coarse sediments.

Figures 20 and 21 show the works already in place overlaying the air photo of the site.

The upper dams (BF-1 and BF-2), one in each stream, were designed to retain large blocks and break the energy. Both are concrete dams founded in rock. Going downstream, the B-5 dam reduces the peak discharge from 620 to 416 m³/s. It is 16 m high and founded in rock. Two other dams, BS-1 and BS-2 (deformable structures built with steel frames filled with rockfill, settled on alluvium), reduce the peak discharge further to 334 m³/s at the entrance of the large reservoir W-10. The reservoir W-10, plus the smaller upper reservoirs formed by the dams, can retain up to about 160,000 m³ of sediments.

The water with fine sediments flowing out of the spillway is conducted through channels, galleries, and an emergency lateral spillway to a natural stream that brings the water to a stilling basin to sediment the fines before the clear water is discharged into the nearby river. These works are described in more detail in a paper by Cruz et al. (2004).

Complementary works

As the impact forces on the dam structures are difficult to predict with precision because of the many unknowns involved, an inclined rockfill cushion upstream of the structures was provided as additional protection at some dams. Both the inclination and the deformability of the rockfill tend to absorb a great part of the impact force. The stability analysis of the dam took into account impact forces acting horizontally against the dam.

In the case of the “breaker” dam BF-2, alternating slots and concrete blocks, a curved upstream profile was adopted for the blocks to help dissipate the impact forces by directing the flow upward. Besides, the concrete blocks were protected with steel plates to reduce effects of abrasion and impact of stones.

In the case of the “steel frame” filled with rockfill (dams BS-1 and BS-2), the downstream slab was made in a similar way as the dams, 1 m thick and 9 m wide (Fig. 22).

Immediately downstream from the “subdams” of BF-2, BF-1, and B-5 dams, at the end of the dissipation basin of the concrete dams, a downstream concrete slab was included. Additionally, to avoid the effect of regressive river erosion, which could affect the slab, a flexible mantle of reinforced gabions was built at the toe of dams BF-2 (Fig. 23) and B-5. The gabions are 1 m thick, reinforced with steel bars in both directions and fully completed with cement mortar in the voids to avoid their destruction in case the wire mesh is hit by a rock block. They are separated one from another to allow flexibility but tied together by steel cables or chains to maintain the integrity of the mantle. In the last rows of alternating gabions with voids, tetrahedrons made of steel bars were installed and tied to the neighboring gabions, which trap rock fragments of decimetric sizes of the flow. Completing the mantle, “stars” made of steel bars tied together at the center were also tied with cables to the mantle of the gabions. With erosion of the riverbed downstream, the mantle of gabions deforms until an equilibrium profile is reached, preventing regressive erosion.

Other low-cost works were also undertaken. To reduce the contribution of riverbed material, upstream from BF-2 dam, seven “stone collars” were built along the Pedras stream, perforating large rock boulders existing at the site, above 1.5 to 2 m in diameter, linked by steel cables anchored in 10-m-long drill holes at the river banks. Such collars (Fig. 24) retain rock fragments and create steps in the riverbed. These “stone collars” were adequately spaced to protect the natural riverbed deposits from erosion.

In two locations where bank erosion was occurring, concrete walls embedded in the alluvial foundations were built. In other river stretches, rockfill made of stones of large diameters and cemented with mortar were built along the banks, providing substantial savings.

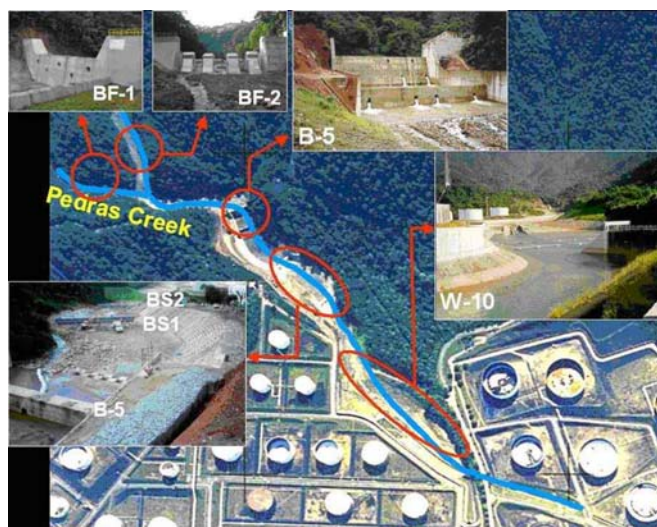


Fig. 20 Control works for Cubatão Refinery, Brazil—upstream of W10 reservoir



Fig. 21 Control works for Cubatão Refinery, Brazil—downstream of W10 reservoir



Fig. 24 Example of a stone collar



Fig. 22 Downstream view of a steel frame type dam (BS-1)



Fig. 25 Gabions with reinforced shotcrete protecting the lateral dyke between the B-5 and the BS-1 dams



Fig. 23 Flexible mantle of reinforced gabions



Fig. 26 Vertical steel bars to retain trees and vegetation

The protection of an existing lateral earth-rockfill dyke downstream of dam B-5 and the abutments of the dams BS-1 and BS-2, consisted of gabions 0.5 m thick, 1.5 m wide, and 3 m long, placed in steps and covered with 10-cm-thick shotcrete reinforced with steel mesh, with 2-m-long perforated drain tubes (Fig. 25).

Finally, to retain tree logs, tree branches and leaves that fluctuate on the top of the moving mass and could trap the spillway of W10 reservoir, two structures were built. The first is a set of vertical steel rails, 3 m high, spaced 2 m from one another, fixed atop a concrete base, buried in the riverbed between BS-1 and BS-2 dams (Fig. 26). The second structure is composed of two lines of floating drums with meshes, linked by cables that were anchored in shafts installed in the margin of W10 reservoir in front of its spillway.

In the northwest and west basins, where other debris flows have occurred, Petrobrás built four higher gabion dams. Complementary works still to be undertaken consist of reinforcing each of the downstream dams with rockfill on the upstream face; and, downstream from both basins, an earth dam with concrete spillway will be built to break the peak discharge. These works will complete the protection of the refinery.

Conclusions

The Cubatão region is prone to recurrent debris flows, considering the high, steep slopes covered by tropical residual soils from gneiss and colluvium, and intense rains that constitute the main triggering factor of landslides and debris flows. Based on rain records, a criteria for determining triggering rains for landslides and debris flows is proposed, with correspondent levels of severity. It is also shown that the 1-h rainfall has a relationship with the total area of slides with respect to the basin area.

The observation of the landslides, erosion, and deposits allowed the understanding of the mechanism of the debris flow. There is a relationship between boulder sizes and stream inclination. The volume of sediments was calculated from the cleaning operations and by air photo analysis, confronted with theoretical and empirical formulae. The Japanese empirical formula reflected with good approximation the amount of solids with respect to the basin area, as well as the use of Takahashi's expression for solids concentration of 0.5. The peak discharge was well estimated for this and for other cases by a new expression, modified from that of Araya Moya. These estimations and a debrisgraph, similar to a hydrograph, developed for the 1995 and 1996 events, allowed establishing design parameters for protection works to future debris flows.

The dams designed and built as protection works aimed at the progressive reduction of peak discharge and accumulation of transported solids. The dams follow, in part, Japanese experience and, in part, Austrian experience in controlling debris flows. However, some other low-cost and innovative works against erosion were built as special gabion slabs and walls, cemented rockfills, stone collars, and steel barriers and floating drums linked by cables to retain branches and avoid clogging the reservoir spillway.

Some other works are to be built in the northwest and west basins to complete the protection of the refinery.

List of symbols

A	basin area
A_e	slipped area
b	channel width
c	solid concentration per unit volume
c^*	c value for the channel deposits
d_{50}	average grain size
e	the mean depth of the slip surfaces
g	acceleration of gravity
H	maximum difference in height within the basin
I	intensity of rain in millimeters/24 h
I_1	amount of rain in the hour that precede the debris flow
L	total length of torrent
p	the volume of torrent bed and bank deposits as a percentage V_s
q_0	specific discharge flow
q_T	peak discharge of a debris flow
Q_0	flood water discharge
V_s	debris flow volume of solids (sediments)
V_T	total volume of the debris flow
γ_0	mud density (water plus clay and silt)
δ	particle density
η	soil porosity
ϕ	friction angle of the granular material
θ	slope angle

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