November 1973

Erosion Control: Stability of Rock Sausages

Chesley J. Posey
University of Connecticut

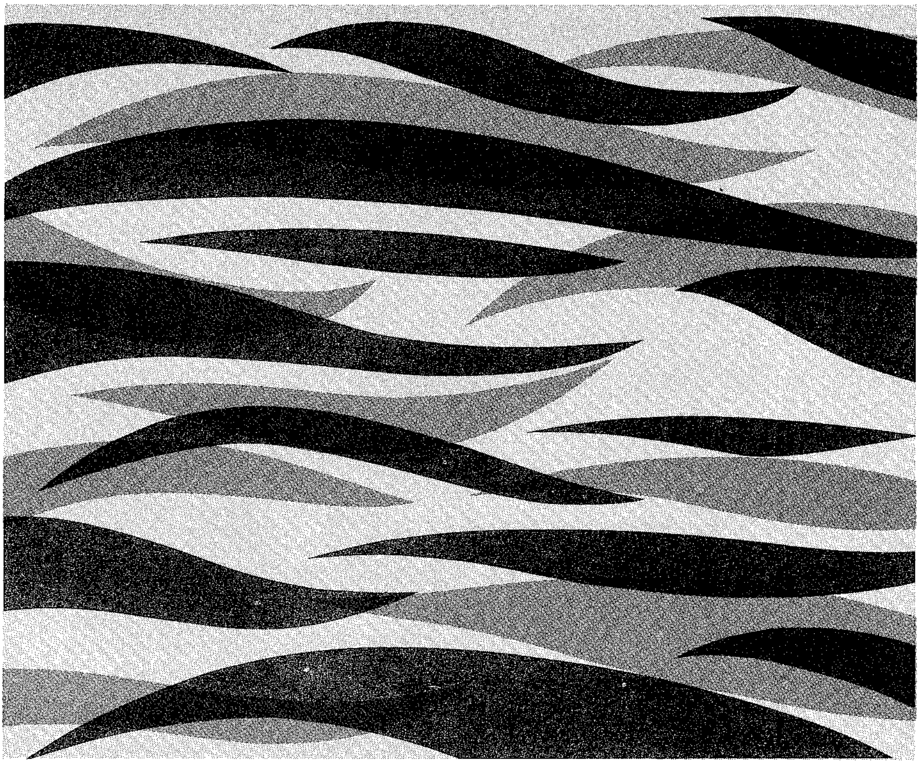
Recommended Citation
Posey, Chesley J., "Erosion Control: Stability of Rock Sausages" (1973). *Special Reports*. 17.
http://digitalcommons.uconn.edu/ctiwr_specreports/17

EROSION CONTROL:

Stability of Rock Sausages

Report No. 19

November 1973



Institute of Water Resources
The University of Connecticut

Report No. 19 November 1973

EROSION CONTROL:
STABILITY OF ROCK SAUSAGES

by
CHESLEY J. POSEY
Professor of Civil Engineering
The University of Connecticut

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964, Public Law 88-379, through The University of Connecticut Institute of Water Resources Project A-035-CONN.

TABLE OF CONTENTS

INTRODUCTION

Rock sausages were invented by the Chinese many centuries ago. They were originally trumpet-shaped bamboo cages filled with headsized rocks, and were used for temporary dams, to divert streams, and otherwise protect against destructive currents. Breaks in the levees of the Yellow River were closed by having hundreds of men roll in long rock sausages, nearly six feet in diameter, with heavy wire cables extending upriver to secure anchorage points. Recently the Chinese have stopped the flow through channels subject to powerful tidal currents by rolling giant sausages from the decks of boats. They have placed miles of riverbank revetments made with wire-bound rock sausages placed in tight rows.

It is evident that the Chinese have considerable experience with rock sausages. What we don't know is whether they have formulated criteria that will permit them to predict the size of sausage that will resist being moved by a given depth and velocity of flow. The project reported here was planned to investigate this problem by means of model tests. Although rock sausages have not as yet found much use in the United States, an increase in their use can be expected. Mechanized manufacture and handling will reduce the cost. Less rock is needed than for riprap, and smaller sizes can be used. Especially where rock is scarce this gives an advantage over the alternatives of concrete or asphalt. If washed out by unexpectedly heavy flows, sausages can be salvaged and used in rebuilding. They can be used again and again when needed for temporary protection.

Increasing concern over the loss of soil by erosion, with consequent sediment pollution of streams, has heightened interest in developing inexpensive ways of protecting against erosion. Fortunately, a method of installing rock sausages so as to prevent fine material from being washed out from underneath (an action called "leaching") has recently been developed.[3] There is no evidence that the Chinese have learned of this improvement, although they apparently do know how large the sausages must be to avoid being moved by the current, and under what circumstances they need to be anchored. Investigations to determine the size of loose rocks or riprap required to resist a given boundary shear have been reported in the United States.[1] They yield a wide range of results, which is to be expected because of the different possible shapes and surface roughnesses. The use of rocks is not recommended when the longitudinal slope of the stream is greater than ten percent; it is already known that rock sausages can be used on slopes as great as fifty percent.

SUPPLEMENTAL LEACHING TESTS

It was decided to start the investigation of rock sausage stability in the same inclined jet impingement apparatus which had been used to find out how leaching of the finest-grained non-cohesive soils could be prevented by covering them with properly graded inverted filter layers. Before modifying the apparatus (shown in Fig. 1) it was deemed necessary to make an additional leaching test which is reported briefly here. In a report on inverted filter tests made at the Waterways Experiment Station, the opinion was stated that a filter which protected a certain fine material, about 50 percent of which would pass an 0.05 mm screen, would also protect any finer material.[6] The writer's tests have already substantiated this conclusion for several very erodible fine-grained non-cohesive materials.[3] As a general conclusion it should also apply to cohesive materials. To test this, a layer of stiff gray clay was placed in the inclined jet apparatus. Unprotected, it eroded very slowly. The erosion seemed to be more by flaking rather than by surface wearing, which seems to confirm the theory that with dynamic pressure

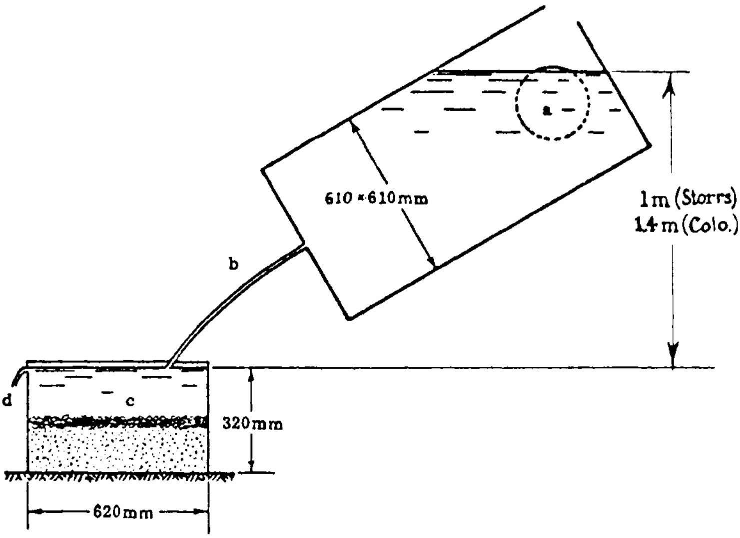


Fig. 1 – INCLINED JET IMPINGEMENT APPARATUS
- (a) Supply from constant head tank
- (b) Jet
- (c) Glass-sided plunge pool
- (d) Overflow to drain, 310 mm wide

Dimensions shown are for the apparatus at Storrs. The apparatus at Allenspark was twice as large.

transmitted through minute cracks to a location under a low pressure zone, flakes are broken upward. It took 90 minutes for the maximum depth of erosion to reach 11 mm (erosion of fine sand, under the same exposure, would be instantaneous, since the jet was capable of moving 40 mm to 50 mm rocks).

When the gray clay was covered with a 13 mm layer of graded sand (presumably capable of protecting any material finer than D_{50} = 0.05 mm) and a 15 mm layer of graded pea gravel under a layer of 28 mm plastic mesh tubes filled with 5 mm to 10 mm pea gravel, no erosion could be detected after a run lasting 386 hours. (It seems likely, therefore, that the generality of the Waterways Experiment Station authors' hypothesis will ultimately be confirmed. Only water-soluble soils would need to be excluded.) A third run was made with the 28 mm sausages placed directly over the clay, without the underlayers to prevent leaching. The clay was eroded to a depth of 6 mm after 225 hours of exposure.

STABILITY OF ROCKS AND SAUSAGES COMPARED UNDER IMPACT OF INCLINED PLUNGING JET

When the tests described above had been completed, the fine material was removed from the bottom half of the plunge box of the inclined jet apparatus and replaced by pea gravel. The stability of rock sausages was to be compared with that of loose rocks, and it was believed that the porosity of the thick layer of pea gravel would provide easy passage of the pressure pulsations induced by turbulence generated by the jet. For most of the tests pea gravel was covered with a tight level layer of 15 mm diameter sausages. (Use of a sheet of plastic mesh as a substitute for the layer of sausages was tried but soon abandoned, since the pea gravel below it was displaced, requiring relevelling.) The various stones and sausages to be tested for stability were placed on top of the level layer. When the jet was started, observed movement might be almost immediate complete displacement, a period of wiggling followed in time by complete displacement, wiggling continued without appreciable displacement over a considerable length of time, or no motion whatsoever. Inasmuch as both rocks and sausages could be placed in a variety of orientations and positions, many tests had to be made before the minimum sizes judged to be stable could be determined. The stability of rock depended upon its shape and orientation in the flow. The time required for each test, varying from less than an hour to several hours, prevented making enough tests to justify a statistical study of shapes and sizes.

The sausages were less variable in shape than the stones, but orientation was more important, since a single sausage, placed perpendicular to the axis of the jet, would roll easily. It was decided that the stable size for sausages would be considered to be that which resisted movement of the edge sausage of a tight row perpendicular to the jet axis, or the end of a sausage in the parallel position. Similarly, the comparable stone was that on the exposed edge of a layer of stones.

In addition to the tests run in the inclined jet apparatus at Storrs, an additional series was run in apparatus twice as large, built for the purpose at the Rocky Mountain Hydraulic Laboratory, Allenspark, Colorado. Although geometrical similarity was preserved in most dimensions, the sausages forming the level bed were 75 mm in diameter and the gravel underneath 15-25 mm. Because the stones to be tested in this apparatus were heavy and the jet strong it was impractical to install a glass side to the plunge box. This limited the observations, for it was impossible to detect motion while the jet was running. If the stone or sausage was seen to be in the same position after flow was stopped, it was recorded as being stable.

Rocks used in the smaller apparatus were selected by sieving (for example, passing 3 inch square mesh but retained on 1½ inch) but were also measured and weighed, both surface dry and submerged. Those for the larger apparatus were hand picked. While shapes varied, there were almost no very flat rocks and few elongated ones. The rocks were all smooth, somewhat rounded stones and boulders of igneous origin, picked up from streams eroding glacial till. The diameter of a spherical rock having the same volume as each was computed, and it is the average of these values, designated Φ_{av} of rocks, that is given in Table I, which summarizes the results of all the tests. The first 80 tests, run in the smaller apparatus, indicate that rock sausages, under comparable conditions, are as stable as rocks with Φ values twice their diameter. The remaining 128 tests, run in the larger apparatus, do not maintain quite as large a ratio. Different orifice diameters were used to change the severity of the exposure. During each set of comparisons, however, the head on the jet was carefully kept constant. That on the larger apparatus was $\sqrt{2}$ times that of the smaller, giving double the jet velocity.

Table I. – STABILITY OF ROCKS AND ROCK SAUSAGES PLACED ON LEVEL PERMEABLE BED AND EXPOSED TO ATTACK OF INCLINED JET PLUNGING THROUGH POOL

Diameter of orifice mm	Q $\frac{\text{liters}}{\text{sec}}$	V $\frac{\text{meters}}{\text{sec}}$	Θ	Depth of pool mm	Smallest stable sizes, in millimeters			
					Φav of rocks	(Number of tests)	Diameter of sausages	(Number of tests)
18.4	.55	4.44	50°	170	42	(12)	15	(6)
19.0	.58	4.45	50°	170	48	(8)	16	(7)
26.3	1.11	4.51	50°	165	60	(27)	24	(21)
50.8	6.4	5.70	48°	340	108	(33)	51	(29)
76.3	14.3	5.67	51°	305	148	(15)	82	(8)
101.6	25.5	5.65	49°	310	162	(23)	$\geqslant 82$	(20)

STABILITY OF ISOLATED ROCK SAUSAGES AND SOLID ROCKS EXPOSED TO HIGH VELOCITY FLOW OVER CONCRETE APRON

A concrete flume 2 meters wide was provided with a head gate which could be adjusted so as to discharge a sheet of water 30, 35, or 46 mm thick with a velocity of about 3.5 meters per second. The longitudinal slope of the flume was 0.0045, and while it had originally been trowelled smooth, years of weathering had exposed some of the aggregate so that it could no longer be classed as smooth, but neither could it be said to be very rough, since the exposed particles were not sharp, but rounded, and the deviations from a plane surface were mostly narrow crevices not more than 1 or 2 mm deep. The experiment was designed to determine whether rock sausages would be moved by this flow, and to compare their performance with that of rocks of various sizes and shapes.

After a given flow condition was established, a rock or sausage was placed about 0.9 meter downstream from the head gate in what seemed to be the most advantageous orientation with respect to the flow. In the case of the nearly round sausages, this was obviously with the axis of the sausage parallel with the flow. Other orientations were not tried for the sausage except when it was accidentally misplaced. A deviation of only five or ten degrees would result in its rolling sideways.

In testing rocks, it was found that the shape of the rock is of great importance. Some rocks would roll unless placed in a certain orientation, while other lighter rocks could withstand the current in any of several positions. Some heavier rocks would roll immediately, no matter how positioned. Rounded rocks rolled most easily. Those that had a flat bottom were at an advantage, and it was obvious that rocks with several flat faces and oblique sharp corners actually benefited from a downward component of the dynamic force. The numerical values are shown in Table II.

Table II – STABILITY OF ISOLATED ROCK SAUSAGES AND SOLID ROCKS EXPOSED TO HIGH VELOCITY FLOW OVER CONCRETE APRON – 1971

Test	Velocity meters/sec	Depth mm	Froude No.	Rocks stable in some position		Rocks stable in any position	
				No.	Wts (kg)	No.	Wts (kg)
7/3	3.60	30	6.7	25	0.58-2.85	5	2.83-6.55
7/5	3.5	35	6.0	8	4.1-8.8	4	9.0-13.2
7/6a	3.36	46	5.0	3	9.0-13.2	1	13.2
7/6b	3.55	46	5.2	1	13.2		

The 13.2 kg rock of the 7/6b test measured 152 by 213 by 280 mm. It rolled or slid from most positions in which it was placed. Making dependable observations had become increasingly difficult with the larger rocks and stronger flows, so that it was not practical to find the range of values

appropriate to each category, as had been done in the 7/3 and 7/5 tests.

The sausages, which were of black polyethylene mesh filled with 6 to 19 mm mostly rounded stones to an outside diameter of about 80 mm, were tested under each of the flow conditions shown in the table. In every case they remained motionless when aligned within a few degrees of the direction of the current. The sausages were 500 to 555 mm long and averaged 5.2 kg in weight. The upstream ends were fused plastic mesh with corners rounded to about 15 mm radius.

Inasmuch as the resistance of the sausages to being moved was surprisingly great in comparison with all but the most advantageously shaped rocks, tests were made to determine the static friction of sausages and of rocks against the wet bottom of the flume. The horizontal force required to start the sausages in motion, as determined by a spring balance, was from 2.2 to 2.7 kg, indicating a coefficient of static friction of about 0.5. For the large rock that moved only in the last run, it was 0.65. For another rock it was 0.72. For the flow conditions 7/6b, where the sausage remained motionless but seemed nearly ready to move, the computed weight equivalent ρQV of the jet sheet against its frontal area below the depth of 46 mm was 3.85 kg. Since this is greater than half the weight of the sausage it seems that the dynamic force on the sausages had a downward component. This was evidenced by the fact,that much water was thrown vertically upward at the nose of the sausage. No similar comparison seems possible for the rocks. In almost all cases, the stable rocks or sausages deflected the flow so completely that the depth of water alongside and downstream was only a few millimeters.

One year after the above tests had been completed, higher flow in the

Table III – STABILITY OF ISOLATED ROCK SAUSAGES AND SOLID ROCKS EXPOSED TO HIGH VELOCITY FLOW OVER CONCRETE APRON – 1972

	Flow Condition			
	V=3.85 m/s, y=35 mm, F=6.6		V=3.76, y=46 mm, F=5.6	
	No. tested	Wt. in kg	No. tested	Wt. in kg
Heaviest rock unstable in every position	6	10.4	4	6.8
Rocks stable in one or more positions	19	1.8 to 17.3	10	9.3 to 24.4
Lightest rock stable in every position	1	11.8	1	25.4
Sausage stable if placed parallel to current	1	5.4	1	10.9

stream from which the flume supply was drawn permitted further testing under nearly the same conditions. Most of the tests were of rocks that would only remain stable in one or two positions. No special effort was made to find either the heaviest rock that would be displaced, no matter how it lay, or the lightest rock that could not be moved by the current. The limiting values reported for these categories in Table III are therefore not as well established as those for the probably more significant intermediate group. All rocks were in the specific gravity range of 2.4 to 2.6.

With rocks exposed under uniform conditions showing so much variation, it is easy to see why, in natural streams where the transitory dynamic forces available to move the rocks are less susceptible to evaluation and some rocks may be securely nested while others teeter, any quantification of the conditions for incipient motion must include a very large stochastic component. When aligned with the current, unanchored sausages remained stable against flows capable of moving rocks more than twice their weight.

COMPARISON OF FALL VELOCITIES

The ability of particles resting on the bottom of a stream to resist being moved by the current is considered to have some relationship to their fall velocity. It must be a very complicated relationship. For example, flat-shaped particles descend in an erratic manner, with low average velocity, but when they form the bed of a stream they may arrange themselves in a shingle pattern having resistance corresponding to a comparatively high velocity. Although the fall velocity of sausages, as compared with that of stones, could not be expected to provide a valid comparison of relative resistance to movement on the stream bed, a series of tests of fall velocities was made at the Hydraulics Research Laboratory of The University of Connecticut.[5]

A 200 mm diameter pipe 4.9 meters long was fitted with a wire basket which could be held at various fixed depths below the water surface. The stone, sausage, or mortar cylinder approximating the shape of the sausage was released at the water surface and the time taken to impact on the wire basket measured with a stop watch. Each test was repeated at least five times. The terminal velocity was obtained from plots of average time versus distance traveled beyond that required for acceleration. (See Fig. 2) Check runs made with glass and steel spheres (with the velocities corrected for wall effect, assuming that the corrections given by McNown for laminar flow would also apply to turbulent flow)gave results for drag coefficients that agreed fairly well with values given in standard textbooks.[2] Because of the erratic descent paths the stones, sausages, and occasionally the spheres would hit the smooth walls of the pipe. Unless the impact was heard to be especially hard, the drop was not repeated. This was more because a loud noise was apt to

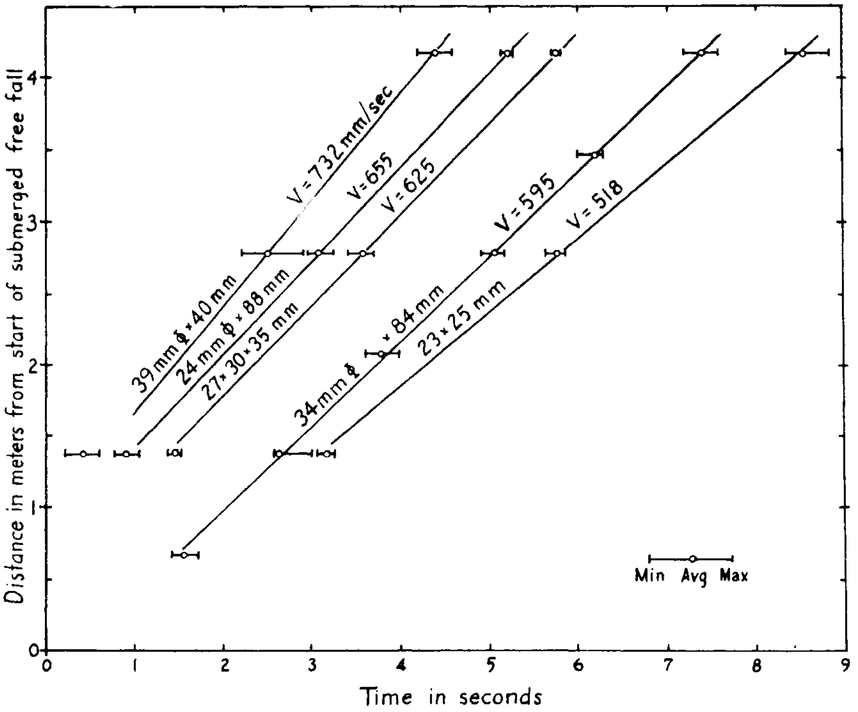


Fig. 2 DETERMINATION OF FALL VELOCITIES OF ROCK SAUSAGES
After the acceleration period, points lie along a straight line with slope equal to the velocity. To avoid confusion the four lines starting at 1.37 meters have each been displaced horizontally.

prevent accurate recording of the time of impact on the basket than to accompany slowing of the fall.

The results, summarized in Table IV, show that rock sausages have lower fall velocities than solid rocks of similar shape. Only the fall velocities of mortar similars, when corrected for the difference in submerged weight (assuming turbulent wakes), are lower than those for rock sausages. It is not believed that this result has much significance with respect to the stability of rock sausages exposed to stream-bed currents, but it may be important where sausages have to be dropped into place through considerable depths.

DESIGN TO OBTAIN STABILITY

Inasmuch as the stability of rock riprap cannot be predicted reliably, the results which relate the stability of rock sausages to that of rocks would seem

Table IV – COMPARATIVE TERMINAL FALL VELOCITIES (After Soong)

	Submerged weight (grams)	Sphericity $\sqrt[3]{(\frac{b}{a})^2 \frac{c}{b}}$	Reynolds Number 10^4	Fall Velocity mm/sec	Relative fall velocities corrected for weight $V \sim \sqrt{\text{submerged wt}}$
Cylinder, L/D = 2.47					
Rock sausage 34/34/84mm	62.5	0.405	1.81	595	1.00
Cement mortar 36/36/85mm	109	0.424	2.40	732	0.93
Long thin cylinders, L/D = 3.67 & 2.96					
Rock sausage 24/24/88mm	46	0.273	1.41	655	1.00
Cement mortar 26/26/77mm	51	0.338	1.35	579	0.84
Short cylinder, L/D = 1.0					
Rock sausage 39/39/40mm	36	0.975	2.56	732	1.00
Cement mortar 40/40/40mm	63	1.000	3.12	870	0.90
Rough semi-spheroid					
Rock sausage 27/30/35mm	15	0.815	1.68	625	1.00
Cement mortar 25/25/32mm	13	0.780	1.57	702	1.20
Small odd shapes					
Rock sausage 23/25mm	7	0.920	1.07	518	1.00
Cement mortar 18/20/23mm	6.8	0.870	1.09	610	1.20
Rock 17/20/29mm	11	0.635	1.82	702	1.08
Rock 18/20/26mm	11	0.730	1.92	823	1.27
Rock 17/18/22mm	7.5	0.796	1.32	671	1.25

to offer little guidance for the designer. It has been found that there is an advantageous size ratio of about two, however, and that rock sausages show less variability. By incorporating information obtained in previous rock sausage investigations,[4] a safe design procedure can now be worked out. Figure 3 represents the forces acting on a unit length (and width) of rock sausage, together with its underlayers. W is the combined weight of sausage, filter layers, water, and soil down to a possible slip plane. σ_s and τ_s are the effective soil pressure and shear values at the plane judged most likely to slip. Forces on the ends of the free body are assumed to cancel except for the increment of tensile force dT in the strands of the sausage mesh. The magnitude of W is easily estimated. The value of τ_w depends upon the velocity and depth of flow. If the flow is fully developed turbulent flow at uniform depth (which is most unlikely), τ_w is equal to $\gamma y S_0$, where γ is the

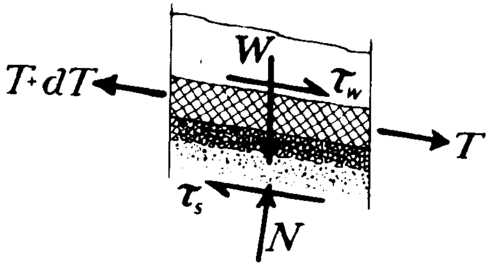


Fig. 3 – Forces Acting Above Slip Plane

unit weight of water, y the depth of flow, and S_0 the slope of the water surface, energy gradient, and sausages. In practical cases, these slopes will not be identical and the flow will not be at a uniform depth. Estimating the important value of τ_w, then, can be done conservatively by first computing the highest value of the velocity that can occur, then assuming that the shear is the same as it would be for uniform flow at that velocity, so that

$$\tau_w = \gamma n^2 V^2$$

The value of Manning's "n" to be used is that appropriate for the rock sausages. Shivarudrappa recommends "n" values for sausage laid parallel to the flow; 0.018 for 57 mm plastic mesh sausages and 0.022 for 90 mm wire mesh sausages.[4] A value of 0.025 should be on the safe side for larger sausages.

With τ_w determined the stability of the installation depends upon a soil mechanics investigation of the probable slip plane and available shear resistance of the soil τ_s. If the soil has low shear strength, a tensile force dT will be required. If so, means of anchoring the sausages have to be investigated. The soil mechanics part of this computation will depend upon the properties of the soil to be protected. Only where soils have low shear resistance or where slopes are unusually steep will this special study be necessary.

REFERENCES

1. Anderson, Alvin G., Amreek S. Paintal, and John T. Davenport, "Tentative Design Procedure for Riprap Lined Channels", National Cooperative Highway Research Program Report 108, 1970.
2. McNown, John S., and Jamil Malaika, "Effect of Particle Shape on Settling Velocity at Low Reynolds Number", Transactions American Geophysical Union, Vol. 31, No. 1, February 1950.
3. Posey, C. J., "Erosion Prevention Experiments", Proceedings XIIIth Congress, International Association for Hydraulic Research, Vol. 2, 1969, pp 211-219.
4. Shivarudrappa, Kudige, "Friction Flow Over Bound-Rock Erosion Proofing", Report No. JHR 66-5, Department of Civil Engineering, University of Connecticut, 1966.
5. Soong, Hsiang-Kuei, "Rock Sausage Fall Velocity Experiments", M.S. Thesis, Department of Civil Engineering, University of Connecticut, 1972.
6. U. S. Waterways Experiment Station, "Laboratory Investigation of Filters for Enid and Grenada Dams", Technical Memorandum No. 3-245, January 1948.

ACKNOWLEDGEMENTS

Mr. Hsiang Kuei Soong assisted at both locations of the experiments, and Dr. William B. Moeller provided volunteer assistance during the 1972 tests at Allenspark, Colorado.