TSUNAMI HAZARDS: ENERGY DISSIPATION AND IMPACT MITIGATION USING BIO SHIELDS

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Abstract: Tsunamis can cause severe destruction in coastal areas. Though the tsunami hazard itself cannot be mitigated nor eliminated, the vulnerable element can be protected by a variety of mitigation measures. Bio shields, including coral reefs, coastal sand dunes and vegetation have been known to provide protection against tsunami inundation. The protection provided by bio shields was evident after the Indian Ocean Tsunami in 2004 in many of the countries affected. In view of these circumstances, attention was focused in this study to identify the capacity of protection provided by bio shields. Small scale physical model tests have been carried out to identify the mitigation characteristics of bio shields in the form of coastal vegetation. This study focused on detailed analysis of the results obtained by model tests. The protection capacity offered by the vegetation was assessed by considering two aspects, namely energy dissipation and reduction in the extent of inundation.

Keywords: Tsunami Hazards, Coastal vegetation, Energy Dissipation, Impact Mitigation

1. Introduction

A large percentage the world population lives in coastal areas and this population is increasing with urbanization. Tsunamiscan be a significant threat to coastal communities as the impacts caused could be both severe and widespread. The impacts caused by a tsunami may spread along hundreds of kilometres.The protection provided by bio shields was evident after the Indian Ocean Tsunami (IOT) in 2004 in many of the countries affected.Bio shields, including coral reefs, coastal sand dunes and vegetation have been known to provide protection against tsunami inundation.

In view of these circumstances, attention was focused in this study to identify the capacity of protection provided by bio shields. The protection capacity offered by the vegetation was assessed by considering two aspects, namely energy dissipation and reduction in the extent of inundation.

2. Tsunami Hazards in Sri Lanka

Although, in Sri Lanka, tsunamis have not been considered as a natural hazard in the past, the IOT and the subsequent tsunami alerts issued in 2005, 2007, 2010 and 2012 have highlighted exposure of Sri Lanka to such hazards. Tsunamis can be generated by a variety of causes but the majority (more than 85 %) is caused by undersea earthquakes. When the geographical location of Sri Lanka is considered relative to the undersea earthquake prone regions, it is evident that the country is exposed to potential tsunamis generated at two such zones, the Sunda Trench located to the east and the Makran Fault located to the northwest in the Indian Ocean.

3. Tsunami Impact Mitigation

Dealing with a possible disaster/risk is three fold, the hazard itself can be prevented, the impacts can be mitigatedor the vulnerable element can be prepared to face the hazard. In the context of tsunamis, the prevention of the hazard is beyond the human capabilities.

Thusit would be appropriate to mitigate impacts and reduce the deficiencies in preparedness of vulnerable elements.

In view of the infrequent nature of tsunamis affecting Sri Lanka and the widespread extent of the coastal area inundated in 2004, it is evident that the development and utilization of bio-shields would be effective in developing appropriate tsunami impact mitigation measures for the country.Such methods would also have the advantages of being cost effective, environmentally friendly and sustainable. Similar to tsunami dykes, sand dunes were effective in intercepting the oncoming tsunami and protecting the sheltered areas whereas the adjacent areas exposed due to the absence of sand dunes, or sometimes due to the artificial removal of sand dunes, suffered severe destruction. Coral reefs are effective in dissipating wave energy. Coastal erosion problems, probably due to coral mining are evident in south western regions of Sri Lanka. The severe tsunami damage suffered by these areas has also highlighted the possible adverse impacts of coal mining in the region.The forces resisting the tsunami induced overland flow due to vegetation are effective in dissipating the energy of flow leading to reduction of the extent of inundation.

4. Tsunami Impact Mitigation by Coastal Vegetation

From a hydraulic point of view, the flow through vegetation can be considered as flow around a group of non-streamlined solid bodies. In fluid flow around a solid body, the energy dissipation takes place due to drag and inertia resistance offered and Hiraishi and Harada (2003) found that tsunami inundation heights can be reduced by 40% by coastal vegetation

Other advantages are also provided by coastal vegetation. By the use of vegetation,coastal areas can be protected from adverse winds and storm surges as well. The cost of developing coastal green belts will be much less than that of many other impact mitigation measures and also the use of vegetation will help the coastal eco systems and will enhance the aesthetic appearance of the coastalareas.

5. Methodology of Study

Ratnasooriya, Bandaraand Samarawickrama(2008)classified coastal vegetation under four different categories based on their physical components (stem, aerial roots, branches and leaves) which facilitate the reduction of tsunami inundation as illustrated in Figure 1.

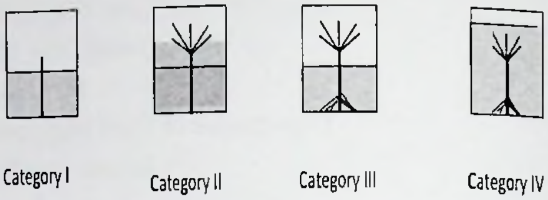


Figure 1: Classification of vegetation

Category I depictvegetation where the resistance is offered only by the stem of the tree. Category II shows vegetation where the resistance is offered by both the stem and the branch system of the tree. Category III is for vegetation with areal roots (mangroves). Category IV is for vegetation where the branch system, stem and aerial roots offer resistance to the flow.

Physical model studieshave been carried out for category I type vegetation. A 1:100 scale model has been used for the study and thevegetation was represented by nails of different diameter. Model studies have been carried out to assess the energy dissipationand impact mitigation due to reduction in inundation.

5.1 Energy Dissipation due to Coastal Vegetation

The energy dissipation of flow through vegetation is due to the resistive forces offered by it. These resistive forces are a combination of drag and inertia forces as expressed by equation (1).

$$F_T = F_D + F_I \quad \text{...}(1)$$

where F_D is the drag force and F_I is the inertia force.

The drag force is proportional to the kinetic head and can be expressed as,

$$F_D = C_D \frac{1}{2} \rho A U^2 \quad \text{...}(2)$$

Where C_D is the drag coefficient and A is the area of the object normal to the flow direction. U is the flow velocity.

The inertia force is proportional to the mass and fluid acceleration can thus be expressed as,

$$F_I = C_m \rho v \ddot{u} \text{...(3)}$$

Where C_m is the inertia force coefficient, u is the fluid velocity and $\ddot{u}$ is the flow acceleration.

The horizontal acceleration, a_x of a wave as for the liner wave theory can be expressed as,

$$a_x = agk \frac{\cosh(kz+kd)}{\cosh(kd)} \sin(kx - \omega t) \text{............(4)}$$

Wherethe variables have their usual meanings.

However, for tsunami induced overland flow caused by long waves of large periods up to even one hour or more, the accelerations are smaller and the inertia resistance can be neglected in comparison to the drag resistance. It can thus be considered that the energy dissipation of flow through vegetation is predominantly caused by drag resistance.

In order to determine energy dissipation characteristics, small scale (approximately 1:100) physical model studies have been conducted in a hydraulic flume of length 10 m, width 30 cm and depth 30 cm. The vegetation has been represented by small scale geometrically similar configurations and water had been allowed to flow under steady conditions as shown in Figure 2.

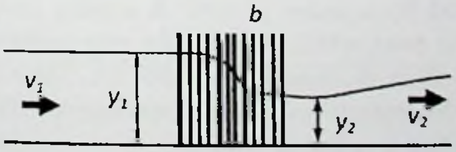


Figure 2: Energy dissipation due to flow through vegetation

Neglecting frictional head loss and the bed slope over the short length of vegetation, the head loss due to the presence of vegetation dH can be expressed as:

$$\Delta H = (y_1 - y_2) + \frac{Q^2}{2gB^2}\left(\frac{1}{y_1^2} - \frac{1}{y_2^2}\right) \text{...........(5)}$$

The parameter dH/H % was used to represent the energy dissipation where H is the upstream head and Q is the flow rate.

5.2 Impact Mitigation due to Coastal Vegetation

Ratnasooriya et al (2008) conducted unsteady flow tests to investigate the tsunami impact mitigation characteristics of coastal vegetation. These have been conducted in the same hydraulic flume in which the steady flow tests were conducted in this investigation. Unsteady flow conditions in the flume have been generated by suddenly releasing water contained in a tank in the flume by the opening of a gate simulating a 'dam break' and water has been allowed to run over a sloping surface. Coastal vegetation has been represented by the same small scale model configurations used in the steady flow tests. The experimental set-up is shown in Figure 3.

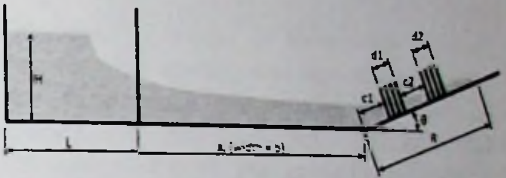


Figure 3: Experimental test setup for impact mitigation

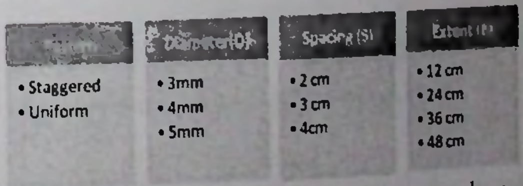
The impact mitigation, duo to the reduction in inundation distance was assessed by the ratio

$$dR/R_0 = (R_0 - R)/R_0 \text{...(6)}$$

where R_0 refers to the inundation distance without the presence of vegetation.

6. Energy Dissipation Characteristics of Coastal Vegetation

Four parameters of the vegetation were considered for the analysis of the relationship between the energy dissipation and vegetation characteristics. The pattern, spacing , diameter and extent of the vegetation were the parameters used. Tests have been carried out for following values of each parameter.



[illegible]	Diameter(D)	Spacing (S)	Extent (E)
• Staggered • Uniform	• 3mm • 4mm • 5mm	• 2 cm • 3 cm • 4cm	• 12 cm • 24 cm • 36 cm • 48 cm

The effect of each parameter is discussed as follows.

6.1 Effect of Pattern

To study the effect of pattern of vegetation on energy dissipation tests have been conducted foruniform and staggered patterns of vegetation withthe other parameters kept constant. Figure 4 shows the variation of energy dissipation variation with the pattern. It can be seen from Figure 4 that, in general, the staggered pattern has given higher energy dissipation than the uniform pattern, although the difference between the two patterns are not very significant. The deviation of energy dissipation of the staggered pattern relative to its counterpart, uniform pattern varies within a narrow range between 0.9 and 1.3.

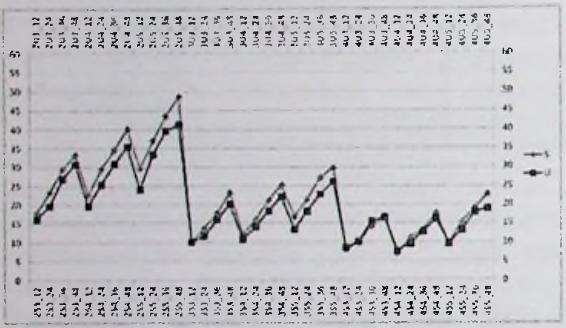


Figure 4: Energy dissipation variation with pattern

6.2 Effect of Spacing

In order to study the effect of spacing on energy dissipation, three graphs (for three D values) were plotted for increasing extent, normalized by theprimaryextent of 12 cm and the spacing of 4 cm in each of the tests.

The graph shown in Figure 5 is plotted for D=3. The same pattern was observed for D=4 and D=5 tests.

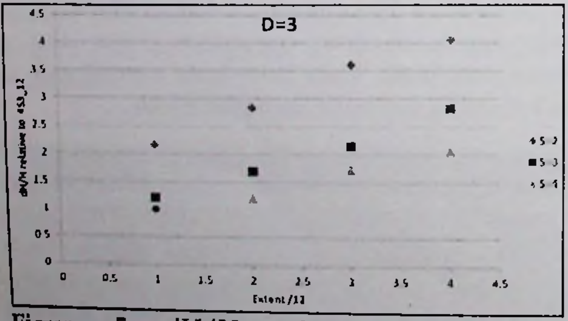


Figure 5: dH/H values,normalized by theprimaryextent dH/H values

The results for the analysis for the spacing reduced from 4 to 2 (spacing halved) is given in Table 1.

Table 1: Energy dissipation values for original and halved spacing

Diameter	Extent increase							
	1		2		3		4	
			Spacing					
	Original	Halved	Original	Halved	Original	Halved	Original	Halved
3	1.00	2.15	1.20	2.84	1.70	3.60	2.00	4.00
4	1.00	3.17	1.56	4.16	1.86	4.87	2.47	5.64
5	1.00	3.03	1.56	3.77	1.94	4.43	2.31	4.96

From Table 1, it can be observed that, for any diameter, when the extent is increased by a certain amount, the energy dissipation will not change by a similar magnitude. In the D=3 test, when the extent is increased by four times , the increase in energy dissipation is only two times that of the initial value. On the contrary, forany diameter, when the spacing is reduced to half of its original value for any extent, the energy dissipation is increased by a magnitude of the order of two. Table 2 gives the incremental values when the space is halved from its original value.

Table 2: Energy dissipation, for space halved

Increase of energy dissipation when space is halved				
Diameter	Extent			
	1	2	3	4
3	2.15	2.37	2.12	2.00
4	3.17	2.67	2.62	2.28
5	3.03	2.42	2.28	2.15

Other than the energy dissipation values when the extent=1 , it can be seen that when the spacing is halved the energy dissipation is increased by a order of two. A similar result was also seen when the spacing was reduced from 4 to 3 (a reduction of 75 %). Table 3. shows the energy dissipation increments when the spacing is reduced by 0.75.

Table 3: Space reduced by 0.75

Increase of energy dissipation when space to 75%				
Diameter	Extent			
	1	2	3	4
3	1.29	1.40	1.26	1.41
4	1.69	1.45	1.60	1.43
5	1.72	1.39	1.42	1.31

From table 3 it can be seen that when the space is reduced by 75% the energy dissipation has increased by a value of the order of 1.3 (4/3).

Thus it can be concluded that,irrespective of the diameter and the extent, the energy dissipation has a direct correlation with the spacing. Furthermore the energy dissipation changes by about the same factor by which the spacing is changed. The abnormal increase in D=4 and 5 at E=1 can be explained under combined influence of space and extent.

6.3 Effect of Diameter

Similar to the analysis carried out for spacing, the effect of diameter on energy dissipation was studied by maintaining the spacing constant and studying the effect of diameter with increasing extent of vegetation. A set of graphs were plotted by normalizing the energy dissipation values obtained by the values for E=12 and S=4 test.

The same pattern of higher energy dissipation for higher diameter was observed for tests S=2 and S=3. The S=4 test results deviate from the other two and gave a mixed pattern (Figure 6). To study this anomaly, energy dissipation graphs for different extents were plotted varying the diameter, which are shown in Figures7 and8.

The same pattern was observed for other extents as well.In the graphs, Figure 7and8, it can be observed that the effect of diameter diminishes as the spacing is increased. At S=4 , the energy dissipation values are approximately the same, irrespective of the diameter. Thus it can be brought forward that unlike spacing, the effect of diameter of vegetation in energy dissipation is influenced by the spacing between the trees.

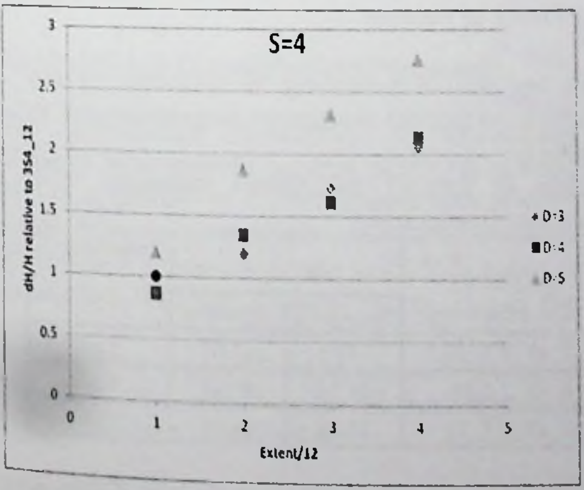


Figure 6: Energy dissipation for S=4

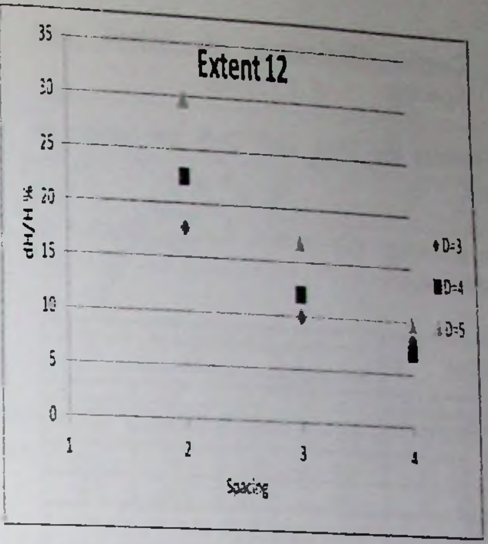


Figure 7: Extent 12 energy dissipation

The effect of extent is influenced by both diameter and spacing and thus to account for the dependency, the combined effect of spacing and extent on energy dissipation with different diameters was considered for the analysis. Graphs were plotted for different D values with increasing extent. Furthermore, theenergy dissipation values of each test were normalized by the energy dissipation value archived at each spacing at the extent of 12 cm. The extent was normalized by the primary extent of 12 cm.

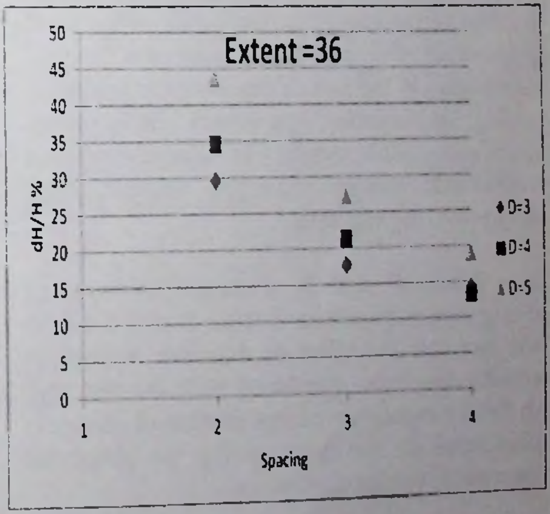


Figure 8: Extent = 36 energy dissipation

6.4 CombinedInfluence of Extent and Spacing

The results for D=4 and D=5 are given in Table 4.

Table 4: Energy dissipation values relative to E=1 test results

D=4		Rate of energy dissipation increase from the 12cm extent energy dissipation value			
Extent increment		1	2	3	4
Spacing	2	1.00	1.31	1.53	1.78
	3	1.00	1.33	1.76	2.08
	4	1.00	1.56	1.86	2.47
D=5		Rate of energy dissipation increase from the 12cm extent energy dissipation value			
Extent increment		1	2	3	4
Spacing	2	1.00	1.24	1.46	1.63
	3	1.00	1.26	1.60	1.75
	4	1.00	1.57	1.94	2.31

From table 4 it can be observed, for both the diameters, the rate of energy dissipation at E=2 for S=2&3 are similar while the S=4 shows a larger increase. It indicates that,although a higher energy dissipation occurs for thicker (closely spaced) vegetation, the increase of energy dissipation when the extent is increased, is smaller than for an increase of extent in sparsely spaced vegetation. This pattern is evident throughout the increase of extent.It is thus apparent that in dense vegetation, a large fraction of the energy is dissipated in the front portion of the vegetation and the energy dissipation in the rest of the extent is less, thus giving a smaller increment in energy dissipation with extent. In sparsely spaced vegetation, energy reduction occurs much deeperinto the vegetation.

In Tables 2 and 3, a larger increase of dissipation is shown for E=1 for D=4 & 5 due to the fact that the effect of diameter is high at smaller spacings, combined with the fact that in thicker vegetation a large portion of energy is dissipated at the front giving an abnormal increase in energy dissipation.

The results for D=3 show a different pattern, indicating a larger increment of energy dissipation for S=4 than S=3 as in D=4 &5. The results for S=4 shows smaller increment (Table 5).

The tests for D=3 and S=4 is among the set of tests that gave the least energy dissipation values. The above stated mechanism for low density vegetation having the energy dissipation distributed throughout the vegetation may not be valid to this set of testsas the energy dissipation that occurs is very low thus deviating from the rest of the tests.

Table 5: Energy dissipation values relative to E=1 test results for D=3

D=3		Rate of energy dissipation increase from the 12cm extent energy dissipation value			
Extent increment		1	2	3	4
Spacing	2	1.00	1.31	1.67	1.87
	3	1.00	1.39	1.78	2.33
	4	1.00	1.20	1.73	2.06

This hypothesis is backed by field studies conductedin the aftermath of IOT by Tanaka etal(2006)where it became apparent, when the spacing was very high, energy dissipation did not occur.

7. Impact Mitigation Characteristics of Coastal Vegetation

Five different vegetation characteristics were taken into account in analysing the effectiveness of coastal vegetation in tsunami impact mitigation efficiency. The parameters that were used are in the equivalent range to those in the energy dissipation analysis. The percentage reduction in inundation distance was selected to assess the amount of impact mitigation obtained. In addition to Pattern of Vegetation (P), Extent (E), Diameter (D) and Spacing(S), the effect due Ground slope (ϴ) was also evaluated.

7.1 Effect of Pattern

The test results indicating the influence of the pattern on impact mitigation is summarized in Table 6.

Table 6: Impact mitigation variation with pattern of vegetation

S,D,E,ϴ,H Combinations	dR/R_0 %		Difference %
	Staggered	Uniform	
2_3_48_7.5_22.5	18.04	17.01	1.03
3_4_48_7.5,25	28.54	27.17	1.37
4_3_48_7.5_25	19.18	16.67	2.51

As indicated in the values shown in Table 6, there is always an increase in dR/R_0% values for the staggered pattern vegetation over uniform pattern vegetation. This beneficial increase lies in the range of 0-5% which is not very significant.

7.2 Effect of Ground Slope (Θ)

Three different slopes have been considered in the tests conducted-1:7.5, 1:10 and 1:12.5. (E_c=12).

The graphs drawn for tests 2S5 and 2S4 are given in Figures9and 10 respectively. There is no notable variation in *dR/R₀%* values with respect to ground slope although it gradually increases with increasing E/Ec values.

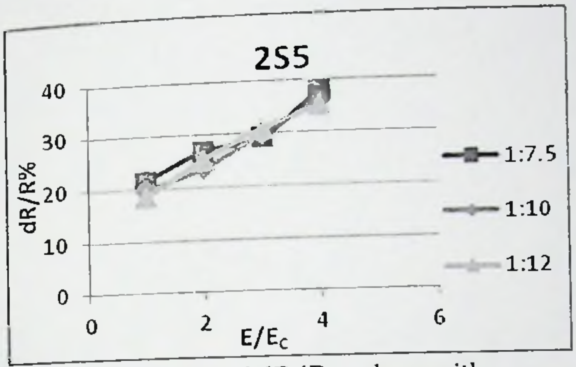


Figure 9: Variation of dR/R_0 values with ground slope

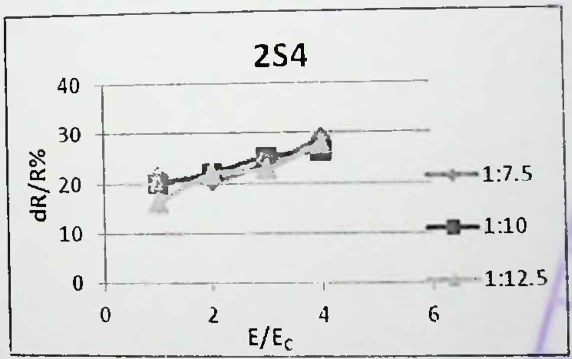


Figure 10: Variation of dR/R_0 values with ground slope

7.3 Combined Dimensionless Parameters

The percentage reduction in inundation distance was plotted against *ED/S²*. A similar variation pattern of *dR/R₀%* values was evident in all three ground slope conditions. Initially, there was a gradual increase in *dR/R₀%* value. It is evident that the *dR/R₀%* values are in the lower range when *ED/S²*=2.5-4.0. This drop is followed by a growth approximately equal to 15%-20%. The effectiveness of the vegetation increases when *ED/S²*>=4.0.

The Figures 11, 12&13show the graphs plotted for the parameters*dR/R*vs *ED/S²*for different slope values.

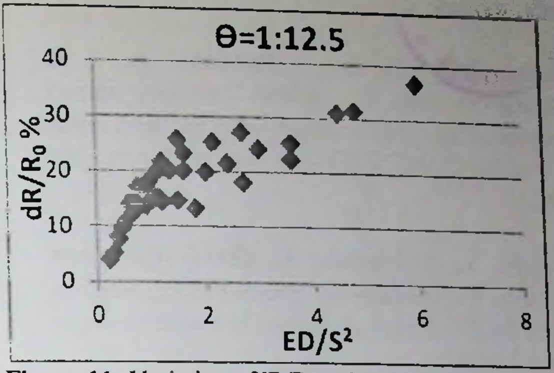


Figure 11: Variation ofdR/R_0 values with ground slope

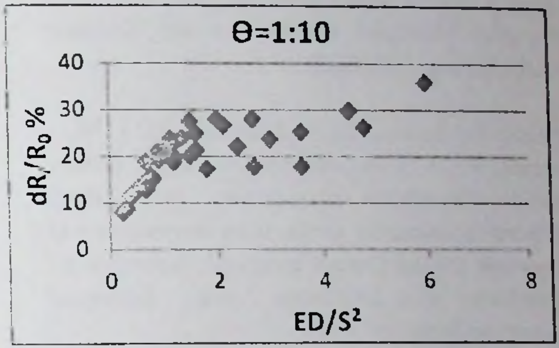


Figure 12: dR/R_0 vs ED/S^2

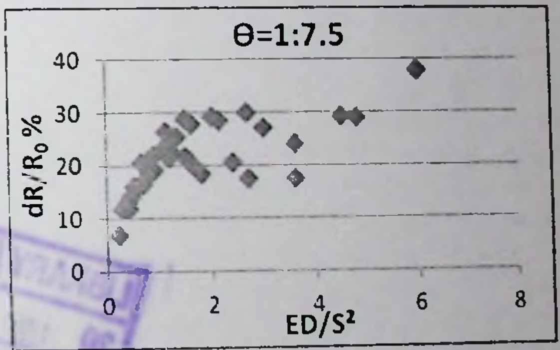


Figure 13: dR/R_0 vs ED/S^2

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