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Susceptibility of Shallow Landslide in Fraser Hill Catchment, Pahang Malaysia

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Abstract

In tropical areas especially during monsoon seasons intense precipitation is the main caused that trigger the natural shallow landslide phenomena. This phenomenon can be disastrous and widespread in occurrence even in undisturbed forested catchment. In this paper, an attempt has been made to evaluate the susceptibility of natural hill slopes to failure for a popular hill resort area, the Fraser Hill Catchment under different rainfall regimes and soil thickness. A Digital Elevation Model (DEM) was prepared for the 8.2 km^2 catchment. A GIS based deterministic model was then applied to predict the spatial landslide occurrence within catchment. Model input parameters include bulk density, friction angle, cohesion and hydraulic conductivity were gathered through *in situ* and lab analysis as well as from previous soil analysis records. Landslides locations were recorded using GPS as well as previous air photos and satellite imagery to establish landslide source areas inventory. The landslide susceptibility map was produced under different precipitation eventûs simulation to see the effects of precipitation to stability of the hill slopes of the catchment. The results were categorized into naturally unstable (Defended, Upper Threshold, Lower Threshold), marginal instability (Quasi Stable) and stable area (Moderately Stable and Stable). Results of the simulation indicated notable change in precipitation effect on Defended area is between 10mm to 40mm range in a single storm event. However, when storm event is exceeded 120mm, the result on Defended area produced by the model tends to be constant further on. For area categorized as naturally unstable (Factor of Safety, SF<1), with 110mm of precipitation in a single storm event and soil depth at 2 meters and 4 meters could affect 69.51% and 69.88% respectively of the catchment area fall under that class. In addition, the model was able to detect 4% more of the landslide inventory under shallower soil depth of 2 meters.

Keywords: deterministic model; landslides; GIS; slope stability; precipitation threshold.

1. Introduction

Landslide is one of natural hazards that often occur all over the world. In tropical climate such as Malaysia, the phenomenon is common especially in hilly areas during monsoon season. Serious natural landslides in this country normally occur in monsoon seasons where intense precipitation is the main triggering factor (Jamaludin *et al.*, 2006). Early indication of the slope stability prone area such as the landslide hazard maps may help planners and developers to choose favorable locations for locating development schemes. Careful engineering and geologic study could then follow before such specific project could be implemented.

There are many approaches to assessing slope stability and landslide hazards (Sidle *et al.*, 1985; Montgomery and Dietrich, 1989; Carrera *et al.*, 1991; Dietrich *et al.*, 1992; Sidle, 1992; Dietrich *et al.*, 1993; Montgomery and Dietrich, 1994; Pack, 1995). Apparently, GIS have become an essential tool for landslide hazard assessment because of its ability to incorporate spatial data input (Huabin *et al.,* 2005; Van Westen, 2000; Gull *et al*., 2008). In area which is faced with high intensity rainfall, it is a well known fact that the hydrological factors may influence to certain degree on slope stability in addition to its geology properties. In this study, a deterministic based model which combined infinite slope method and steady state hydrology was used to delineate potential shallow landslide area within Fraser Hill catchment. There was no previous study on the aspect of landslide prediction for the catchment with the exception of few isolated piecemeal projects (IKRAM, 2007)

1.1. Study Area

The study area is located in Fraser Hill. Fraser Hill is a popular highland resort in Malaysia. Landslides occasion that often occur, may dim its potential as a popular hill resort. The Fraser Hill geomorphology is characterized by hilly terrain and most of the natural slopes are steep with 50° gradients (IKRAM, 2007). The range of elevation in Fraser Hill is from 400 to 1300 meters above sea level. According to (Gassim *et al*., 2001), the mean annual rainfall for the catchment is about 2624 mm with average of 208 rain- days in a year. Based on existing geological map, the catchment and it surrounding is mainly composed by Main Range Granite. The study catchment has an area of 8.2 km^2.

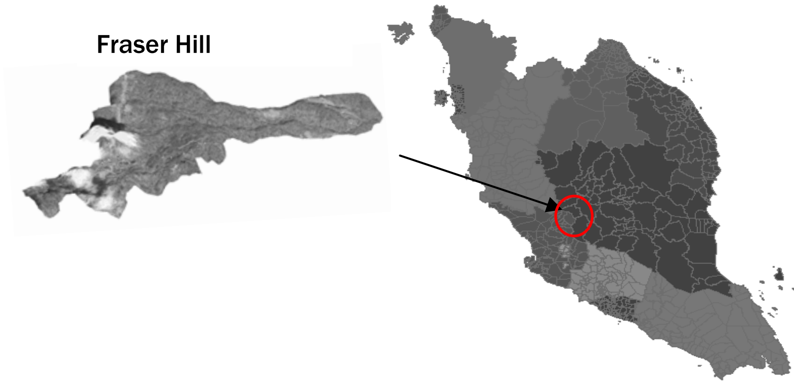

Figure 1. Location of Fraser Hill Catchment (not in scale)

2. Methodology

2.1. Digital Elevation Model (DEM)

Topography of an area is the main factor that controlled the landslide processes. Nowadays, spatial topography can be represented in digital form. Digital elevation model is the digital form that represent the topography of a catchment and it plays an important role in representing the shape of the land surface for landslide study (Carrara & Pike, 2008). DEM can be derived from several techniques. The accuracy of the output of landslide susceptibility map relied heavily on the accuracy of the DEM source itself. In this study, DEM was generated from digital contour digitized from a topographic map in scale of 1:50 000. When exported into the model, the pixel of the DEM was set to 10m x 10m. Fig. 2 shows the DEM for the catchment.

2.2. Model Application and Analysis

A deterministic based slope stability model used to assess the instability conditions and to establish a landslide susceptible map was SINMAP, developed by Pack *et al*. (1998). SINMAP was designed as an extension to ArcView® GIS, a product of Environmental Systems Research Institute, Inc. SINMAP is applied to shallow transitional land sliding phenomena controlled by shallow groundwater convergence (Pack *et al*., 2001). The mathematical models developed by Pack *et al*. (1998) available for studying shallow landslides, take into account the infinite plane slope stability model coupled with a steady state topographic hydrologic model.

The infinite slope stability model factor of safety (SF) (ratio of stabilizing to destabilizing forces) is given by (simplified for wet and dry density the same, from Hammond *et al*., 1992)

$$FS = \frac{C_r + C_s + \cos^2\theta\left[\rho_s g\left(D - D_w\right) + \left(\rho_s g - \rho_w g\right)D_w\right]\tan\phi}{D\rho_s g \sin\theta\cos\theta} \quad (1)$$

Where C_r is root cohesion [N/m²], C_s is soil cohesion [N/m²], θ is slope angle, ρ_s is wet soil density [kg/m³], ρ_w is the density of water [kg/m³], g is gravitational acceleration (9.81 m/s²), D the vertical soil depth [m], D_w the vertical height of the water table within the soil layer [m], and ϕ the internal friction angle of the soil [-]. The slope angle θ is the arc tangent of the slope, S, expressed as a decimal drop per unit horizontal distance. Fig. 3 illustrates the geometry assumed in equation (1).

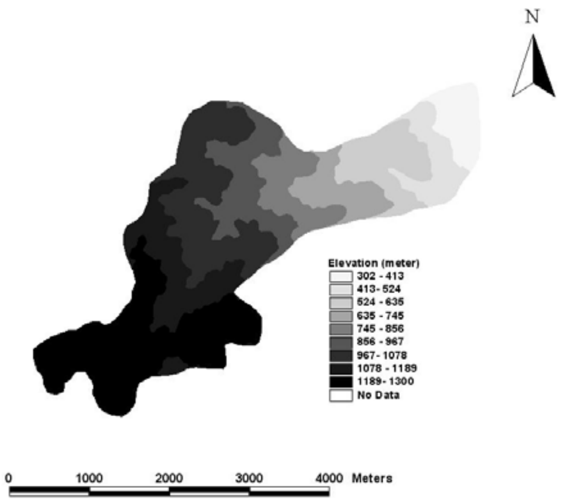

Figure 2. DEM for Fraser Hill Catchment

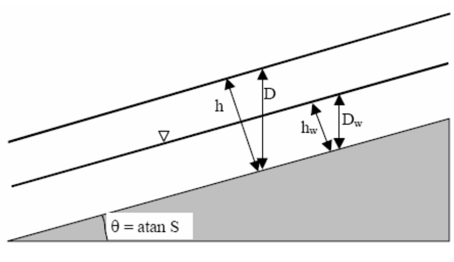

Figure 3. Infinite Slope Stability Model Schematic (Pack *et al.,* 1998)

SINMAP approach with the hydrologic model is to interpret the soil thickness as specified perpendicular to the slope, rather than soil depth measured vertically. Soil thickness, h [m], and depth are related as follows:

$$h = D\cos\theta$$

With this change, FS reduce to:

$$FS = \frac{C + \cos\theta[1 - wr]\tan\phi}{\sin\theta} \qquad (2)$$

Where, $w = D_w / D = h_w / h$ = relative wetness, $C = (C_r + C_s)/(h\rho_s g)$ = combined cohesion made dimensionless relative to the perpendicular soil thickness, $r = \rho_w / \rho_s$ = water to soil density ratio.
The relative wetness index as below:

$$w = Min\left(\frac{Ra}{T\sin\theta}, 1\right) \qquad (3)$$

To define the stability index, wetness index from Eq.(3) is incorporated into the dimensionless factor of safety, Eq. (2) which becomes:

$$FS = \frac{C + \cos\theta\left[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right)r\right]\tan\phi}{\sin\theta} \qquad (4)$$

The variable *a* and *θ* are derived from Digital Elevation Model (DEM) whereas the values of *C*, tan *ϕ*, r and *R/T* are user input. DEM, soil and hydrologic properties and landslide source areas inventory of the catchment are necessary to generate the stability index grid which can be used as landslide susceptibility zoning. In the analysis, the geotechnical input for the model; soil density, friction angle and cohesion were held constant throughout the process. Hydraulic conductivity for the catchment also was held constant but the rainfall events were manipulated using the three precipitation events as shown Table 1. Table 2 shows the geotechnical input applied for this study. In this model, uncertainty factor is applied where the calibration regions are areas within which single lower bound and upper bound of calibration parameters values can represent transmissivity/recharge ratio (T/R), dimensionless cohesion (C), and friction angle (f). In this study, the minimum value of each of these parameters was used as the calibration for lower bound and the maximum value as an upper bound.

2.3. Geotechnical Data

The model required several geotechnical input. The inputs were soil density, internal friction angle and cohesion and soil depth. Soil density was determined in the laboratory by weighing and measuring the volume of undisturbed samples. Internal friction angle value was gathered from an unpublished report of landslide that occurred in Fraser Hill by (IKRAM, 2007). Although there were also other references that produced the result of internal friction angle in Malaysia (Komoo, 1985; Ting *et al*., 1972), the one from IKRAM was used in this study. Soil depth varied all over the catchment and from the interpretation of geologic and soil maps and observation on the actual slope failure location during the *in situ*, we are able to estimate the depth of the soil. Cohesion is another geotechnical input required by this model. The suggested value by the author of the model (Pack *et al*., 1998) for cohesion was applied to this model since there is no available data regarding the parameter for this catchment.

Table 1. Geotechnical input used in this study

Parameters	Value
Soil Density, ρ_s, Kg/m^3	1900
Friction angle, ϕ, °	27 - 36
Cohesion, *c*	0 - 0.25

2.4. Hydrological Data

Hydrological input in this model was in term of wetness index (T/R), ratio of transmissivity (T) (*m*2 / *hr*) of the soil and rainfall recharge into the soil (R). T is the transmissivity or the vertical integral of the hydraulic conductivity of soil and can be determined by:

$$T = (k_s) \times h$$

Where k_s is the hydraulic conductivity of the soils determined in the lab using permeameter while *h* is the thickness of the soil above the failure surface. k_s was determined using constant head method as suggested by Zaitchick *et al*., (2003). These hydraulic conductivity values were then multiplied by the soil depth (*h*). The *h* value was assumed to be constant 2

Table 2. Risk of Landslide according to certain cumulative storm event

Risk of Landslide	Cumulative Rainfall (mm)
No	<30
Low	30 to 60
Medium	61 to 100
High	>100

(Adapted from DID website: http://infobanjir2.water.gov.my/explain.htm)

Table 3. Precipitation events according to risk of landslide classes

Risk of Landslide	Rainfall event in a single storm (mm)
No	10
	20
	30
Low	40
	50
	60
	70
Medium	80
	90
	100
	110
High	120
	130

(Adapted from DID website: http://infobanjir2.water.gov.my/explain.htm)

Table 4. Table of the *T/R* (m) values used for each precipitation threshold in the SINMAP analysis

Rainfall Event (mm)	T/R (m)	
	Lower Bound	Upper Bound
10	84.25	330.60
20	42.13	165.30
30	28.08	110.20
40	21.06	82.65
50	16.85	66.12
60	14.04	55.10
70	12.04	47.23
80	10.53	41.32
90	9.36	36.73
100	8.43	33.06
110	7.66	30.05
120	7.02	27.55
130	6.48	25.43

and 4 meters depths for all over the catchment area (based on average soil depth). Based on lab analysis, the minimum of hydraulic conductivity in Fraser Hill catchment wass 0.035105 *m/hr* and the maximum value was found out at the lower part of the catchment which was 0.137749 *m/hr*. R is the steady state recharge that can be defined as: = Rainfall - (Infiltration + Evaporation) In this study, we adopt the storm events that would trigger landslide as proposed by Drainage and Irrigation Malaysia (DID, 2009). Table 2 showed the classification from DID base on a single storm event.

The DID's classification is based on a single storm event typically ranges from two to four hours of rain. In this analysis, we used all 13 precipitation events within the classification to represents each class of landslide hazard (no, low, medium and high hazard). We attempted to assess which precipitation events triggered most of the catchment area to landslide categorized as Defended (the most hazards area indicates by this model). Table 3 shows the precipitation events used in recharge (R) estimation in this study. Finally, the transmissivity was divided by the recharge rate to define the upper and lower T / R (m) values. The final T / R values used shown in Table 4.

2.5. Landslide inventory

SPOT 5 satellite images were used to identify the possible landslide locations through visual interpretation as well as ground truthing had been done to confirm the specific locations. During *in situ* visit, the coordinate of the landslide location had been taken using GPS. Throughout the *in situ* study, not the entire landslide locations can be accessed due to dense forest and very steep slope. This inventoried data was then used to validate the model prediction.

3. Results and Discussion

Using the DEM and landslide inventory data, the SINMAP model was used to derive a stability index (SI) map. This SI gives the prediction of landslide hazard prone areas in term of Factor of Safety (FS). The SI is defined as the probability that a location is stable assuming uniform distribution of the model inputs over their uncertainty ranges. The range of the SI value is between 0 (most unstable) and 1 (least unstable). Table 5 shows the six stability index classifications in terms of SI values as defined in the model output. The Lower Threshold, Upper Threshold

Table 5. Stability Class Definition (SINMAP User Manual, 1998)

Condition	Class	Predicted State
SI >1.5	1	Stable slope zone
1.5>SI>1.25	2	Moderately stable zone
1.25>SI>1.0	3	Quasi-stable slope zone
1.0>SI>0.5	4	Lower threshold slope zone
0.5>SI>0.0	5	Upper threshold slope zone
0.0 >SI	6	Defended slope zone

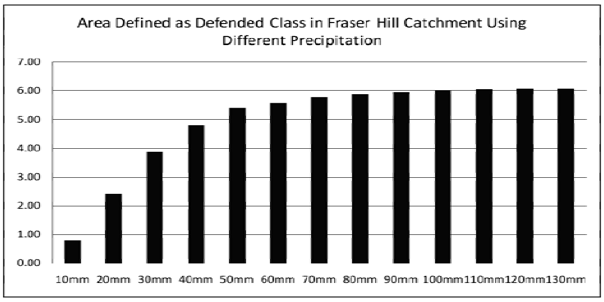

Figure 4. Percentage of Defended area according to different precipitation event for 2 meter of soil depth

and Defended classes have SI values less than 1 and can be grouped as naturally unstable while Quasi-Stable is defined for marginal instability class where the SI values between 1.0 and 1.25. Moderately Stable and Stable class can be considered as stable as they have SI values higher than 1.25.

The results of the simulation for the hazard area according to Defended class was shown in Fig. 4, As expected, with higher precipitation threshold used, the model tend to generate more Defended area. The most notable change of precipitation effect on the hazard area affected is between 10mm, to 40 mm of precipitation. When the precipitation threshold was increased from 40 mm to 120mm, the changes is rather small ranges from 0.04% to 0.62%. However, when the threshold was set at 130mm, it gave the similar results as imposing 120mm of precipitation. It can be assumed that the total area predicted as Defended area will remain constant when the amount of precipitation is more than 110mm.

Fig. 5 showed the Stability Index (SI) grid for Fraser Hill catchment when the soil depth and rainfall are considered at 2 meters and 110 mm respectively. Based on statistical output of the model in Table 6, by holding the soil depth to be constant throughout the analysis at 2 meters and rainfall is 110mm, the model able to predict 65% of the total landslide inventory. At the same time total of unstable area (FS<1) is 69.51% or 5.7 km of the catchment area to be considered. Likewise in Table 7, for soil depth of 4 meters, the model predicted 5.8 km of total area to be considered as naturally unstable. 61% of the landslide inventory was able to recognize by the model.

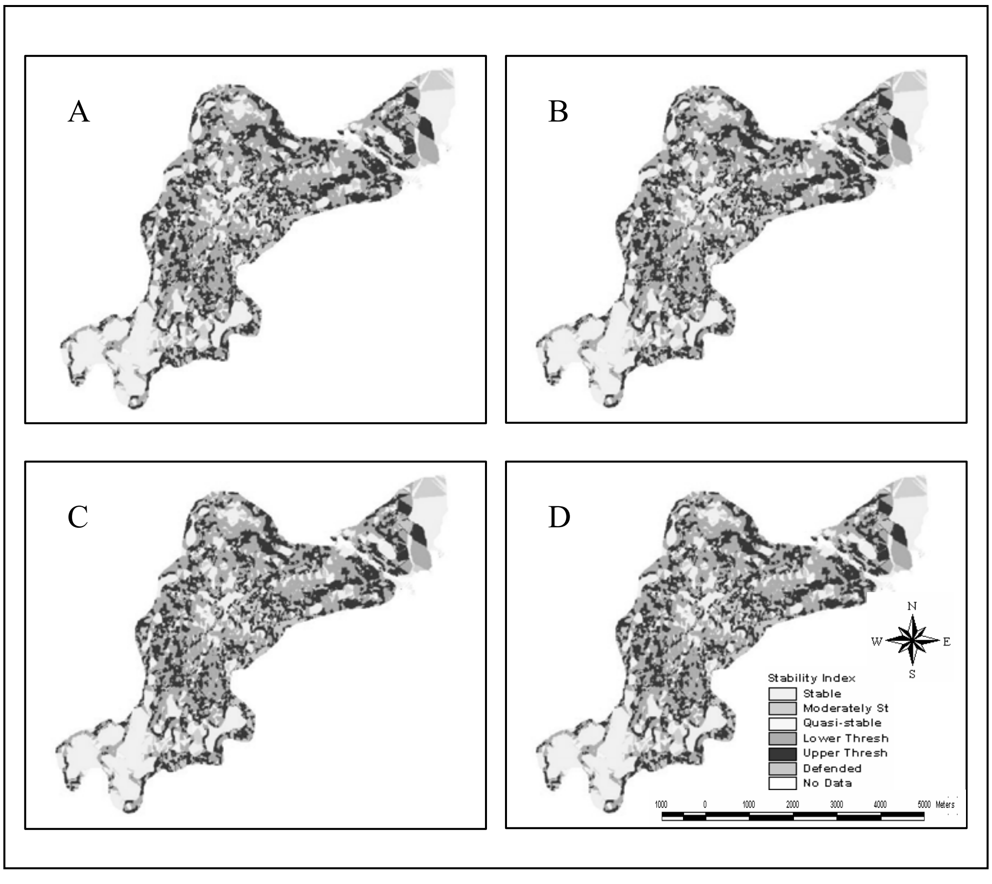

Figure 5. Stability index grid map based on four precipitation events. A, B, C and D represent SI map using 10mm, 30mm, 70mm and 110mm of precipitation respectively. The soil depth is 2 meters.

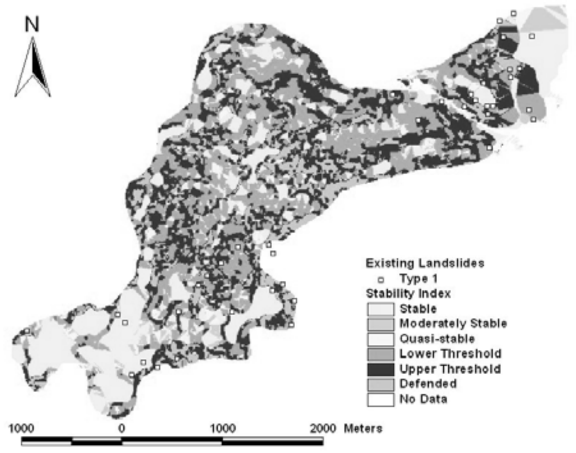

Figure 6. SI map for soil depth equal to 4 meters and rainfall is 110mm

4. Conclusion

Susceptibility of shallow landslide in Fraser Hill Catchment was studied under different rainfall amounts and soil depth using SINMAP model. In this analysis it was found that the model is more sensitive to precipitation event under 120 mm. beyond that the model predicted almost constant result for each type of hazard class. These trends appeared to be the same either using soil depth of 2 and 4 meters. With soil depth of 4 meters, more hazard area was detected as compared to 2 meters soil depth (with difference of 0.37 km^2). However, by using 2 meters of soil depth, the model was able to detect 4% more of landslide inventory compared to analysis using 4 meters of soil depth. The analysis also indicated that with greater soil depth, it will result in more hazard area but did not reflect that it will also able to detect more of recorded/ inventoried landslides. The results of the analysis based on different soil depths to map SI map reflects this scenario. It is important to note that a slope stability map produced in this study indicates the probability of hill slope failure rather than the actual landslide hazard. It is important to note that the landslide susceptibility map produced in this study indicates the probability of hill slope failure rather than the actual landslide hazard.

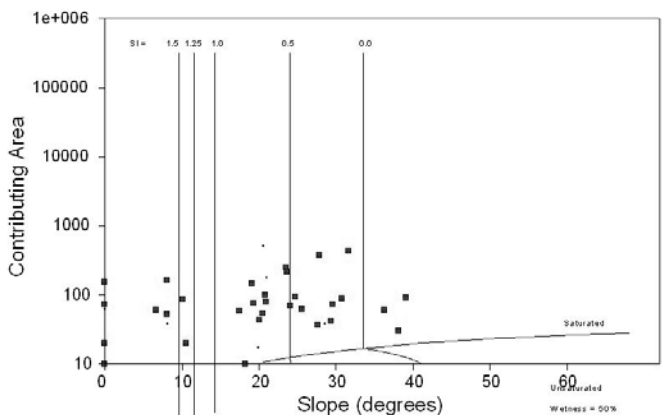

Figure 7. Slope (degrees) - Area (m^2) Plot of Fraser Hill Catchmen Based on the SA plot, 73.5% of the landslide occurred on slope of more than 10 degrees. However there were also landslide occurred in flat areas especially those located in the Fraser Hill town which caused by modification of road. Detailed interpretations of the SA Plot were provided as the statistical summary in Table 6 and Table 7 for 2 and 4 meters soil depth respectively.

Table 6. Statistical summary of analysis using 2 meters of soil depth

	Stable	Moderately Stable	Quasi Stable	Lower Threshold	Upper Threshold	Defended
Catchment (km^2)	8.2					
Area, km^2	1.90	0.20	0.40	2.70	2.40	0.60
% of Region	23.00	3.00	4.30	33.10	29.00	7.60
No. Of Landslides (LS), #	10	1	1	9	10	3
% of LS	29.40	2.90	2.90	26.50	29.40	8.80
LS Density (#/km^2)	5.30	4.10	2.80	3.30	4.20	4.80

Table 7. Statistical summary of analysis using 4 meters of soil depth

	Stable	Moderately Stable	Quasi Stable	Lower Threshold	Upper Threshold	Defended
Region						
Area, km^2	1.90	0.20	0.40	2.80	2.40	0.60
% of Region	23.00	3.00	4.40	33.70	29.00	7.00
No. Of Landslides (LS), #	11	1	2	8	11	3
% of LS	30.60	2.80	5.60	22.20	30.60	8.30
LS Density (#/km^2)	5.80	4.10	5.50	2.90	4.60	5.30

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