Application of a Method for Predicting Occurrence of Slope Failures due to Heavy Rainfalls

by

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A catastrophic rainfall was recorded in July 1983 in the western part of Shimane Prefecture, and serious disasters were caused by the rain. The data on the heavy rain and slope failures is analysed. It is examined how the occurrence of slope failures is related to the rainfall characteristics. The variation of the number of slope failures with time is well correlative with that of the rainfall intensity, some slope failures, however, occurs after the stopping of the rain.

For predicting the occurrence of disasters due to the heavy rainfall, a method using a tank model is applied and critical value of the storage in the tank is determined. It is also shown that the critical storage can well explain the occurrence of disasters and explain the possibility of the delayed failures.

1. INTRODUCTION

A catastrophic heavy rainfall was recorded from the evening of 22nd to the noon of 23rd July 1983 in the western part of Shimane Prefecture, the San-in district. The hourly rainfall reached more than 50mm/h between 0.00 and 1.00 on 23rd and such a rainfall continued till 10.00 on the day. There had never been experienced in this district such a heavy rainfall that the hourly rainfall intensity of more than 50mm/h was recorded uninteruptedly over 10 hours [1]. By this Heavy rainfall, more than one hundred persons were killed or missed and the damage amounted to more than 300 thousand millions yen. The geological, geotechnical and hydrological features of disasters have been made clear [*I]

The purposes of this Paper are to examine and discuss how the time when a slope failure occurred is related to characteristics of the rainfall and, by applying a method for predicting occurrences of slope failures or debris flows to the case of disasters in Hamada City, Shimane Prefecture, to discuss the possibility of preventing disasters due to heavy rainfalls.

2. RAINFALL CHARACTERISTICS AND SLOPE FAILURES

2.1 Characteristics of the Rainfall in Hamada City

The hyetograph recorded from 0.00 of 16th to 24.00 of 24th July in Hamada City [*II] is shown in Fig.1, where the accumulated rainfall is also represented.

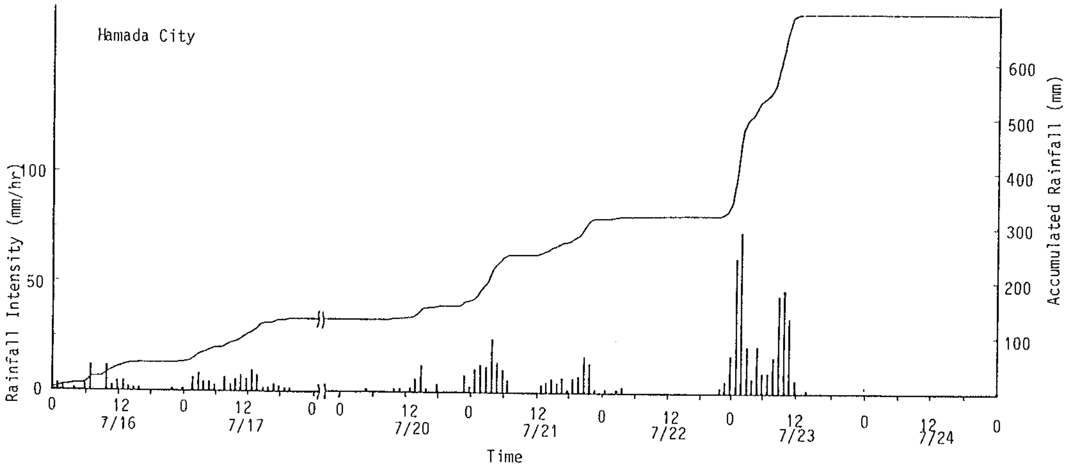

Fig.1 Hyetograph and accumulated rainfall in Hamada City

[*I] Disasters due to this heavy rainfall were investigated and analyzed by research group organized by the support of the Natural Disaster Science Research Foundation of the Ministry of Education. The results have been reported [1]. The first Author also worked in the group as a member and investigated especially the disasters such as slope failures or debris flows occurring in Hamada City.

[*II] The data was obtained at the Hamada Fire Station.

A series of the rain from the noon of 20th to the early morning of 22nd already caused small land slides or slope failures at six sites in the Shimane prefectural area. After this preceding rain ceased, a really heavy rainfall bagan at about 21.00 and the hourly rainfall intensity reached 60mm/h two hours later. It even increased to 70mm/h at 2.00 of 23rd. The rainfall became light a little for several hours, the heavy rainfall, however , again came at 8.00. A series of this heavy rainfall ceased completely by the noon of 23rd. Most disasters occurred in this heavy rain from 21.00 of 22nd to the noon of 23rd.

2.2 Distribution of Slope Failures

Fig.2 shows the distribution of slope failures and debris flows [*I] that caused large and small damages to houses, human lives etc in the municipal area of Hamada [*II]. Other slope failures and debris flows than those shown in this figure are still many but not considered in this study, because it is not known at what time they occurred.

Plots in Fig.2 are more frequent along the rivers than in the mountainous area, particularly along the lower R.Hamada, where the urban area of the city is located, because only slope failures that did some damages are concerned with in the figure. It should be noted here that there occurred many slope failures which did no damage, and that they distribute over the municipal area, even in the mountainous area.

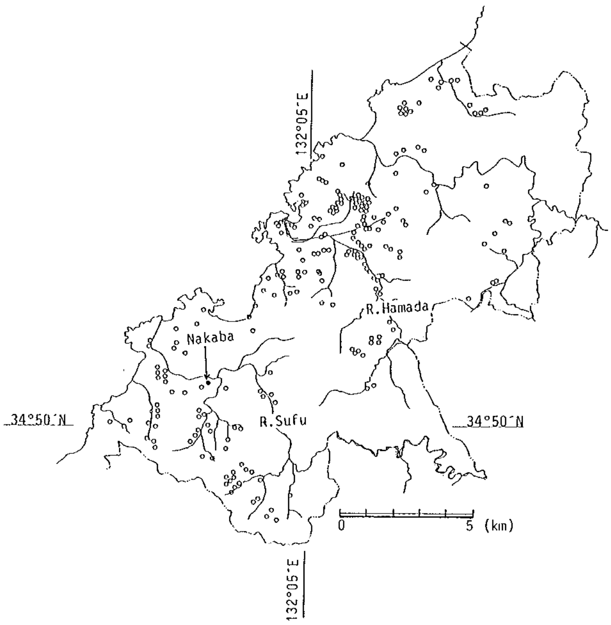

Fig.2 Distribution of slope failures that did some damages in Hamada City.

[*I] In the following, the term "slope failures" is used to include debris flows.

[*II] Slope failures and debris flows that caused damages were investigated by the Construction and Civil Engineering Office of the Shimane Prefectural Authorities, and the data concerning with them have been collected in a report. For each slope failure or debris flow, the time of the occurrence of failure, the length, width, and height of the slope, the damage, the location of the site etc are recorded in the report. The data collected in the report was used and analyzed in this study.

2.3 Variation of the Number of Slope Failures with Time

In Fig.3 the variation of the number of slope failures with time is represented. By a rough comparison of this figure with Fig.1, which shows ths characteristics of the rainfall at Hamada, it is observed that the peak of the number of failures corresponds approximately to the time when the strong rainfall intensity is recorded. The comparison gives an another important finding: an appreciable number of failures occurred after the noon of 23 rd, when the rain had already stopped. For example, large slope slides at Nakaba(the location is shown in Fig.2), which caused the most serious disaster in Hamada by which 15 persons were killed, occurred at 12.00 and 13.00 of 23rd. Thus, some slopes can fail even after the stopping of rainning. This fact must be taken into account in predicting disasters due to heavy rainfalls.

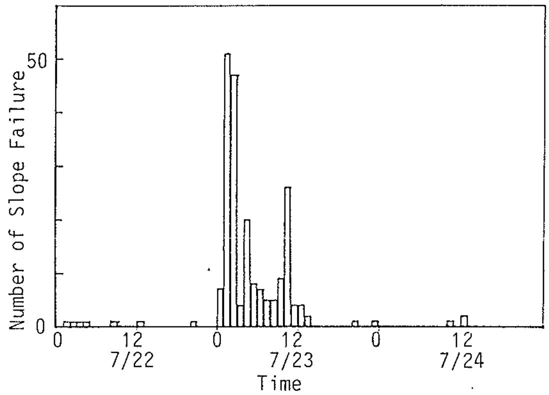

Fig.3 Number of slope failures and the time when the failures occurred

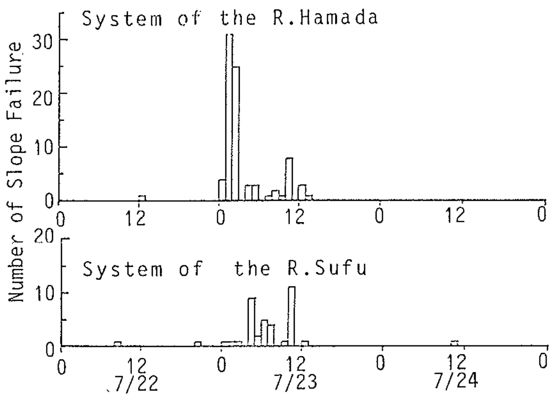

Fig.4 Number of slope failures and the time when the failures occurred for each river system: (a) in the system of the R.Hamada; (b) in the system of the R.Sufu.

It will be examined whether the time when a slope failure occurred is related to or not in which river system the slope is sited. More than 85% of slope failures which gave damages occurred in two river systems of the R.Sufu and the R.Hamada(see Fig.2). Thus, slope failures sited in these two river systems are considered and those in other systems are not.

For each river system, the variation of the number of slope failures with time is shown in Fig.4. In the system of the R.Hamada, the peak of the number of failures is seen at the time between 1.00 and 3.00 of 23rd. On the other hand, in the system of the R.Sufu, it is seen between 10.00 and 11.00 of 23rd. Earlier than this time, i.e. between 4.00 and 5.00, the first-time peak of the number is seen, however, even it is two hours later than the time of the peak in the system of the R.Hamada.

It will be easily supposed that the difference of the variation of the number of failures between these two river systems may be resulted from the difference of the rainfall characteristics between them.

A representative rainfall characteristics for the system of the R.Hamada may be as already shown in Fig.1. Any rainfall record obtained in the system of the R.Sufu, however, was not available and hence the rainfall record measured at Misumu-cho will take the place of that of the system of the R.Sufu.

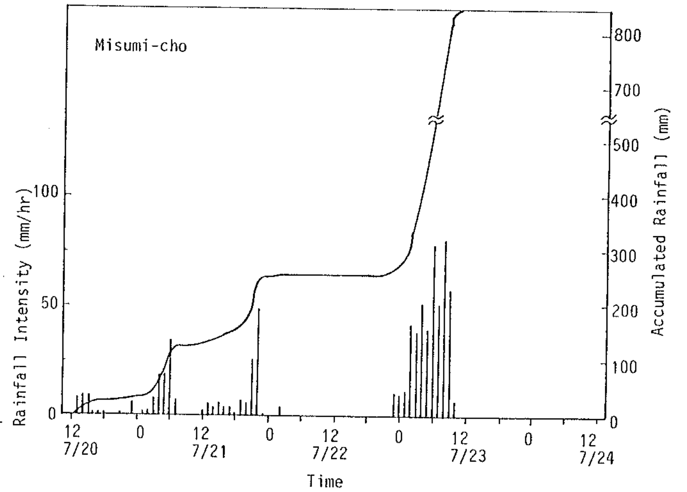

Fig.5 Hyetograph and accumulated rainfall in Misumi-cho

In Fig.5 the rainfall characteristics at Misumi-cho is shown. The hyetograph in the figure is considerably different from that in Fig.1: the first-time intense rainfall more than 50mm/h is recorded from 3.00 to 4.00 of 23rd in Misumu-cho; but that is from 0.00 to 1.00 in Hamada. The fact that the rainfall intensity more than 50mm/h is reached about three hours earlier in Hamada than in Misumi would be able to explain the fact that the peak of the number of slides occurred two hours earlier in the system of the R.Hamada than in the system of the R.Sufu.

3. PREDICTION OF SLOPE FAILURES DUE TO HEAVY RAINFALLS

3.1 Preliminary Consideration

To predict whether disastrous slope failures or debris flows will occur or not in a heavy rainfall is important and necessary for the purpose of preventing disasters. To do so, the characteristics of the rain must be described in terms of some adequate parametrs. Since the rainfall will vary from time to time, such parameters must be some quantities being derived from the up-to-time information on the rain. Among many possible parameters, the hourly intensity of rainfall, the period of raining, the accumulated rainfall, and the effective intensity of rainfall have been considered effective, and, by using one or some of them, to predict the occurrence of disasters has been tried.

It is already clear from the discussion in the preceding section that the rainfall intensity can be of course a very important parameter because the occurrence of disasters is substantially related to it. But the fact that some disastrous slope failures can occur even after the stopping of the rain leads to use it, for example, with the accumulated rainfall.

However, the use of the rainfall intensity with the accumulated rainfall may be limited for predicting the occurrence of disasters. Fig.6 is prepared for the example. This figure is based on the data shown in Fig.1. The accumulated rainfall is shown from 5.00 of 20th July. A series of dashed lines

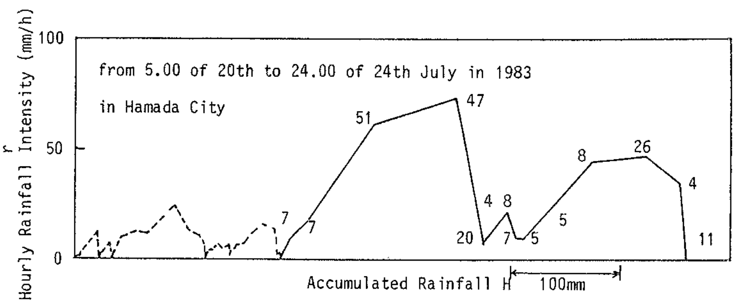

Fig.6 Relation between the hourly rainfall intensity and the accumulated rainfall. Numerals indicate the number of slope failures.

corresponds to the preceding rainfall, i.e. the rainfall from the morning of 20th to the morning of 22nd; and a series of solid lines to the heavy rainfall from 21.00 of 22nd.

The relation as shown in Fig.6 has been used for evaluating the danger of suffering disasters. Namely, a critical line, inside which no disaster will occur and outside which some disasters will occur, has been drawn for some disasters in several districts in the past[3]. If such a critical line is expected to draw in Fig.6, a problem will arise: from when should the accumulation of the rainfall be started? In other words, in the case of Fig.6, how should the preceding rain be treated? For example, when we let the accumulated rainfall be zero at the beginning of the preceding rain, the critical line should be passed near the point of r=0 and H=190. In another way, when we let it be zero at the beginning of the heavy rainfall from 21.00 of 22nd, the critical line will be passed the point of r=0 and H=0. Thus it is very difficult to draw the critical line in the r-H diagram.

Michiue and Kojima[4] analyzed the data on heavy rainfalls that caused slope failures in Kure City of Hiroshima Prefecture since 1951. He used the method using a tank model, one of methods for analyzing the run-off cahracteristics of a bassin, and derived an important conclusion: the occurrence of a slope failure is closely related to the storage in the model at the time of the occurrence. He determined statiscally the critical value of the storage. The critical storage is defined such that , when the value is reached, a high percent of disasters should occurred. An essential feature of this method is to use the storage in the model instead of using directly the data on the rainfall. In the following section, the method using the tank model proposed by Michiue et al[4] will be applied to the case of disasters in Hamada and its ability to predict the occurrence of disasters will be discussed.

3.2 Application of the Method using a Tank Model

(1) Variation of the Total Storage with Time

The total storage in the tanks was calculated every hour by using the hyetograph in Hamada City (Fig.1) and its variation with time is shown in Fig.7. In the figure the dimensions of the tank model and values for parameters used in the calculatoion are also shown. The dimensions and values of parameters are quite the same as those used in the study of Michiue and Kojima[4]. The initial condition is such that: S_t=10; S_1=S_2=0; and S_3=S_t (mm) at 23.00 of 15th July, where S_t is the total storage in the tanks and S_1,S_2 and S_3 are storages in the first tank, in the second tank and in the third tank, respectively. This condition employed here follows the assumption used in Michiue and Kojima[4], and it means that the storage from about 1 week before the first occurrence of disaster is effective.

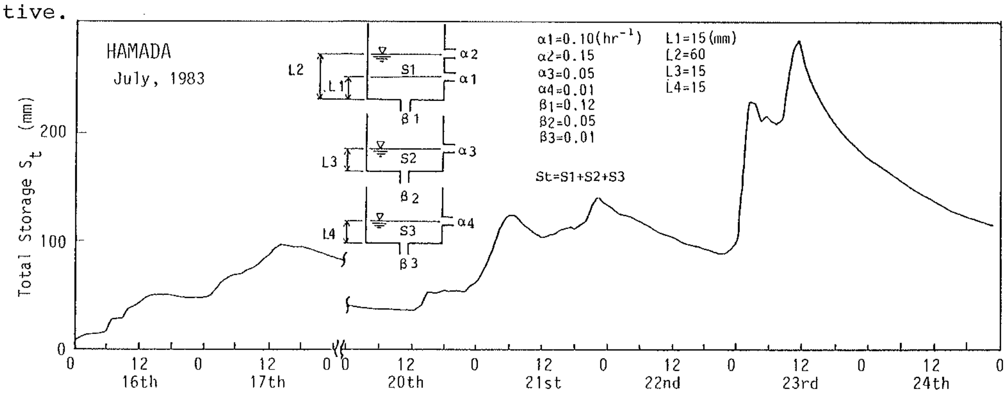

Fig.7 The variation of the calculated total storage with time

It is seen in Fig.7 that the total storage S_t reaches the first-time peak at 22.00 of 21st; it continues to decrease by the midnight of 22nd; and it suddenly increases with a very high rate from the midnight of 23rd. The maximum of S_t is reached at 12.00 of 23rd and after then it decreases.

The behaviour of S_t above will be compared with the hyetograph in Fig.1. The peak of S_t is always reached later than the peak of the rainfall intensity:two hours later in the case of the preceding rain from 23.00 of 20th to 7.00 of 21st; and ten hours later in the case of the disastrous heavy rainfall from 22.00 of 22nd to 12.00 of 23rd. It is also noted that the storage does not run off instantaneously when the rain stopped.

(2) Determination of the Critical Storage

The total storage S_t at any time has been thus calculated, and therefore the relation between the number of slope failures N and the time, as shown in Fig.4, can be converted to the relation between N and S_t. In Fig.8 the result is shown. Since S_t is not a monotonous function of time, two cases when the time rate of S_t can be negative and positivs are distinguished in the figure.

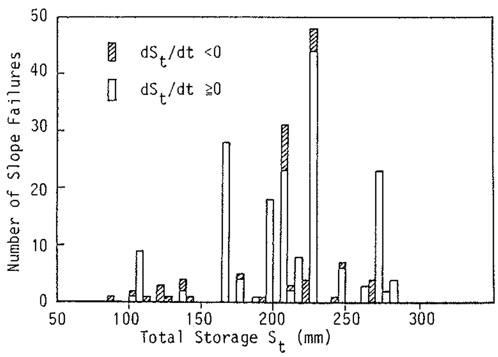

Fig.8 Relation between the number of slope failures N and the total storage S_t.

Fig.8 indicates that, when

the total storage S_t reached a certain value $S_{t(i)}$, slopes of the corresponding number $N_{(i)}$ failed. This implies that the certain value $S_{t(i)}$ can be the critical storage for the slopes of the number of $N_{(i)}$ because they failed when $S_t = S_{t(i)}$. In other words, the critical storage for a slope that failed at a certain time is given as the total storage at that time, and this total storage may be the "local critical storage" S_{tl}.

Fig.8 can be considered as the frequency distribution of the local critical storage S_{tl}. To determine the distribution function is tried in Fig.9, where the relation of N and S_{tl} in Fig.8 is replotted on the normal probability paper. It is clear from this figure that the distribution of S_{tl} can be described by the normal distribution N(μ,σ) where μ is the average value of S_{tl} and σ is the standard deviation . The values for these parameters were determined as μ=200mm , and σ=43mm

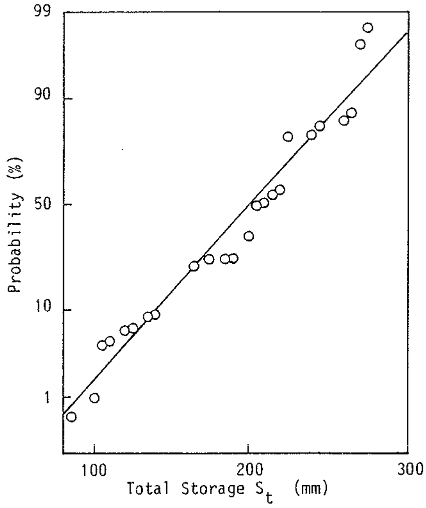

Fig.9. Plots of N-S_t relation on the Normal Probability paper.

In order to predict the occurrence of disastrous slope failures in the area concerned by using the concept of the critical storage, a representative value of the critical storage that can be applied for all the slopes with the potential possibility of failing in the area must be chosen. The representative critical storage for the area concerned, which will be denoted by S_{tc} , should be determined based on the data of many cases in each of which many slope failures occurred. In Hamada City, unfortunately, such statiscal data on disasters in the past is not available. Hence, it is assumed that the relation between the heavy rainfall and the slope failures experienced in 1983 may be typical one.

Michiue and Kojima[4] introduced two concepts for the determination of the value of S_{tc}: One is "the occurrence rate" P and another is "the excess occurrence rate" T. The occurrence rate P is defined as the ratio of the number of slope failures which occurred when $S_t \geqq S_{tc}$ to the total number of failures. The smaller value of the critical storage S_{tc} is chosen, the larger the occurrence rate P will be close to 1. Therefore, the only use of P is not sufficient in evaluating the critical storage S_{tc}. To compensate this unfavorable property of the concept P, an another concept of the excess occurrence rate T was introduced. T is defined as $N_{\Delta tf}/N_{\Sigma\Delta t}$, where $N_{\Sigma\Delta t}$ is the total number of time intervals included in the period when $S_t \geqq S_{tc}$, and $N_{\Delta tf}$ is the number of time intervals in which at least one slope failure occurred in this period.

In the definition of T, a time interval may be reasonably defined as the reference period used in the expression of the rainfall intensity. In this study, a time interval of one hour will be used because the hourly intensity is employed.

When a larger value of S_{tc} is chosen, T will be larger to be close to 1. The larger T is, the more favorable the chosen value of S_{tc} is as the critical storage. Thus, the properties of P and T are opposed from each other for evaluating the value of S_{tc}. Therefore, P and PxT will be used as indices for the evaluation of S_{tc} according to Michiue and Kojima[4].

When the average of S_{tl}, μ, or the value with deviation of $\pm\sigma$ or $\pm 2\sigma$ from μ is taken as the critical storage for the area concerned, P, T and PxT were calculated as shown in Fig.10. From this figure, it would be found that the value of $\mu-\sigma$ could be chosen as the most adequate value for the critical storage S_{tc}, i.e. when $S_{tc}=\mu-\sigma$ P is close to 1, T is not so small and PxT is appreciably large. $S_{tc} = \mu-\sigma$ (=157mm) means from the property of the normal distribution that, when $S_t \geqq S_{tc}$ (=157mm), the S_t should be the local storage S_{tl} in slopes of 84% of those with possibility of failing. In Fig.8 shows that there are 191 slope failures for which S_{tl} is equal to or more than 157mm This number 191 corresponds to 94% of the total number of slope failures.

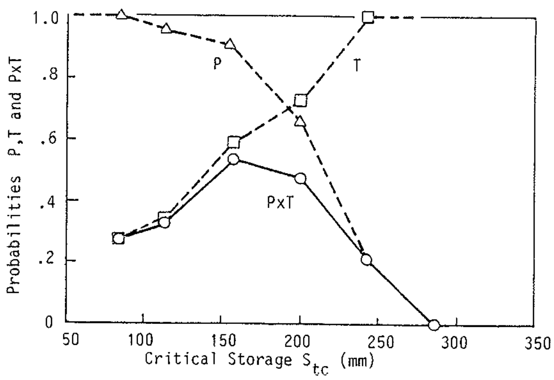

Fig.10 Variation of probabilities with several chosen value of S_{tc}

4. DISCUSSION

The same method as that applied to the case of disasters in 1983 will be applied to the other case of disasters and the ability of the critical storage determined in the preciding section to predict the occurrence of disasters will be examined.

In Fig.11, the hyetograph in Hamada City in 1972 and the calculated total storage curve are shown. The total storage was calculated with the initial condition such that $S_t=S_3=10$mm and $S_1=S_2=0$mm at 5.00 of 9th july. The value of the critical storage of 125mm determined in the preciding section is indicated by a dased straight line. Since the detailed data on the disasters of this case is not available at present, only the data on the road embankment failures are cited based on the published report[5].

In the figure an arrow indicates an occurrence of an embankment failure. The critical storage line can not well explain the occurrences. In facts, 3 failures occur under the condition of $S_t \geqq S_{tc}=157$mm. Thus, the critical storage of 157mm is not so effective for the different rainfall characteristics and for the different type of failures.

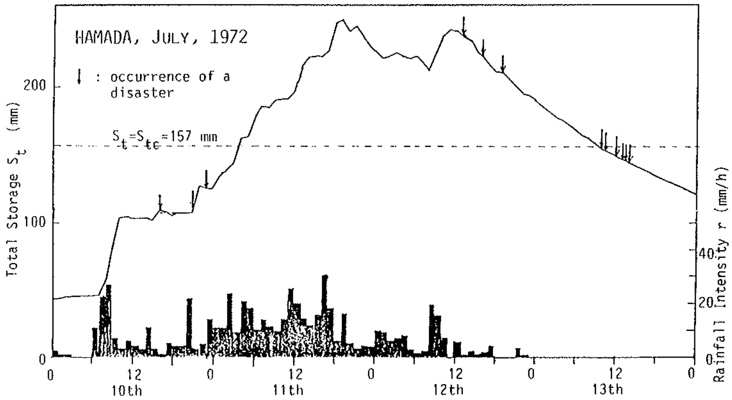

Fig.11 The hyetograph in July 1972 and the calculated total storage.

It has been often emphasized in this study that some disastrous slope failures occurs even after the rain ceases. The example of large slope slides at Nakaba is a typical one.It is said that these slides occurred two times:at about 12.30 and at about 13.00. 15 persons were killed by the slides. It is understood from Fig.7 that, at the time of these slides, the total storage was still higher than the critical value.If the warning had been issued until the time when the total storage has decreased to the critical value, the loss of human lives would be prevented. Thus, the method using a tank model seems to be effective in evaluating the time for issuing the warnig or clearing it.

The method using a tank model has some shortcomings. One of them is that it is affected by the choice of the initial condition, as well as the method using r-H diagram(as shown in Fig.6). In this study, the total storage about one week before the beginning of the heavy rainfall was 10mm based on the assumption made in Michiue and Kojima[4]. The way is rather arbitrary, the following condition, however,will be recommended: the total storage lower than the height of the lowest tank of the model(see Fig.7) should be employed in the period which precedes the heavy rainfall and when the rainfall is null. The effect of the initial condition on the result would not be so much as it may spoil the ability of the method.

5. CONCLUSION

The data on disasters due to the heavy rainfall in July of 1983, in Hamada City of Shimane Prefecture was analyzed in this study.

It was examined how the time when a slope failure occurred is related to characteristics of the rainfall. It was seen that the variation of the number of slope failures or debris flows with time is correlative with the variation of the rainfall intensity with time. It was, however, also emphasized that some disastrous slope failures occured even after the stopping of the rain.

The possibility to draw a critical line in the rainfall intensity-accumulated rainfall diagram was examined, and it was found essentially difficult to do so because of a shortcoming property of this diagram. Instead of the diagram, the method using a tank model, used in Michiue and Kojima[4], was applied to the disasters in Hamada, and the value of the critical storage was determined by using a few concepts of probability. The value determined could succesfully predict occurrences of slope failures.

This method and the derived value of the critical storage were applied to another case of disasters in 1972, and their applicability was examined.

By using the concept of the critical storage, slope failures that may occur after the stopping of the rain can be predicted. The possibility that the loss of human lives due to such delayed failures should have been prevented was shown for the case of slope slides at Nakaba.

In principle, slope failures or debris flows can not be prevented, even though the occurrence would be predicted, because they are natural phenomena. However, the effort to prevent human lives from being lost must be made, and to do so is possible.The method used in this study would be a powerfull for evaluating the time of issuing or clearing the warning agaist disasters due to heavy rainfalls.

Acknowledgements:
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References:
[1] ed.Kadoya,M. (1983):Investigation and Research on Disasters due to Heavy Rainfall in the San-in District in 1983, Report No.58022003, Natural Disaster Science Research of Ministry of Education.(in Japanese)
[2] Shibata,T., Shimizu,M., Yashima,A. and Mimura,M.(1983):"Slope failures and debris flows in Hamada City and geotechnical characteristics of slides at Nakaba",[1], pp.38-49.(in Japanese)
[3] eg.,Egashira,S.:"Disasters due to slope failures and debris flow caused by heavy rainfall of July 1982", Annals of Disaster Prevention Research Institute, Kyoto Univ.,No.26-A, pp.1-17.(in Japanese)
[4] Michiue,M. and Kojima,E.(1981):"Study of forecast for occurrence of land slides due to heavy rain storm", Reports of the Faculty of Engineering, Tottori Univ., Vol.12, No.1, pp.167-178.(in Japanese)
[5] Chugoku Regional Office of Ministry of Construction(1974):Report of Disasters due to Heavy Rainfall in July 1972.(in Japanese)