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INTERDEPENDENCE OF SEDIMENT BUDGET BETWEEN INDIVIDUAL TORRENTS AND A RIVER-SYSTEM

DIE GEGENSEITIGE ABHÄNGIGKEIT DES SEDIMENTSHAUSHALT ZWISCHEN INDIVIDUELLEN WILDBÄCHEN UND EINEM FLUSS-SYSTEM

Artisune TAKEI

Summary

The rules governing the sediment budget in an individual torrent and a total drainage system are not similar. In the former case, almost all movable materials originated from massmovement are washed out from the drainage basin, and the process is regarded as an example of stochastic one. In the later case, the materials supplied from individual torrents to the valleys may be transported corresponding to the hydrodynamic condition of the channel-system, but the stochastic process is moderated considerably to the deterministic one.

We shall have to take those characteristics into account when the comprehensive mitigation measures against sediment disasters will be investigated.

These processes have not been clarified theoretically or by means of a complete simulation model at the present, but there is a large accumulation of observed data on the bygone experiences in Japan, and some of them are applicable to the practical problems according to the proper compiling of the data.

In this paper, some empirical formulae and a basic concept of modelling are proposed and discussed.

Zusammenfassung

Die Naturgesetze, die den Sedimentshaushalt beherrschen, sind in individuellen Wildbächen und einem kombinierten Drainagesystem nicht ähnlich. Im Falle der individuellen Wildbäche werden fast alle bewegbaren Materialien, die durch Massenbewegungen produziert werden, aus dem Einzugsgebiet abtransportiert und der Vorgang ist als ein wahrscheinlichkeitstheoretisches Beispiel zu betrachten. Aber im Falle des gesamten Flußsystems wird der Prozeß deterministischer, weil die Materialien je nach hydrodynamischen Bedingungen von individuellen Wildbächen zu den Haupttälern transportiert werden.

Wenn man eine Präventionmaßnahme gegen Geschiebekatastrophen setzen will, soll man diese Eigenschaften überlegen.

Diese Vorgänge der Geschiebeführung sind bisher weder mit einem komletten Simulationsmodell noch theoretisch aufgeklärt worden. Es gibt aber in Japan zahlreiche langjährig beobachtete Daten und man kann einige davon durch gute Zusammenstellungen praktisch nutzen.

Die Abhandlung handelt von eigen empirischen Formeln und einer gründlichen Idee für das Modellieren.

1. Introduction

The comprehensive plan of erosion control works for each watershed should be considered individually according to the local character of natural and social situation of the concerned area. One of the most important and interesting factors affecting this context is the size of the concerned area. Because the rule governing the relation between them, the volume of sediment production in the source area and the actual sediment yield to downstream reaches are different from each other.

In Japan, for an individual small torrent, a disaster caused by the propagation of massmovement is the major object of public interest in recent years. At the same time, an inundation by sediment laden flood on alluvial-fans and valley-planes hasn't been dissolved even today, not only in the heavily devastated moutainous area but also in almost everywhere seemed to be stable at present, if it be hit by exceptionally heavy rain. In this case, the volume of sediment production and massmovement don't affect directly the actual disasters, but the sediment transport capacity of flood-flow and the character and volume of bed-materials may play an important part in this process.

Although the geophysical interpretation of the phenomena is necessary for the comprehensive understanding of the overall process, it is almost impossible at the present because of the incompleteness of the simulation model including such different processes. However, there is an immense accumulation of official or semi-official reports compiled by administrative agencies and some of them are available as the basic information for scientific researches.

The following consideration is carried out principally by means of the re-compilation of such data, and the reduced result is believed to be fit for practical application.

2. Historical aspect of the problem

In the early stage of erosion control works in Japan, the principal purpose of the works were to maintain a stable condition in downstream reaches of major rivers in order to secure the navigation and irrigation system. Areas developed since olden time, the mountains were denuded or poorly vegetated mostly owing to continuous wild harvesting, at least in the beginning of 16th century. The principal source of sediment originated from the surface erosion in denuded mountains, and the increase of annual sediment discharge was supposed to be the direct cause of the instability of river courses. The people began to reforest the denuded mountains since the second half of 17th century, but they didn't succeed to recover the forest until the beginning of 20th century. In fact, the interpretation of the phenomena and the intention of the countermeasure by the people of those days were proper judging from present scientific knowledge, but they had no technology and orgnization good enough to carry them out.

From the beginning of Meiji Era, the new government endeavored to solve the problem, by then the reforestation techniques on the devastated hill-slope had been developed to almost the some grade as the more contemporary methods used until the first quarter of 20th century.

At the same time, it began to challenge to the stabilization of more actively devastated regions, as the people's demand to prevent sediment disaster was spreading all over the country. However, the traditional techniques of erosion control were not effective enough to prevent the sediment production in such regions, despite the techniques improved as far as their effectiveness in the long-pending troublesome regions where the intensity of the erosion process is moderated with regard to the geophysical situation. Then, since the beginning of 20th century the modern technology of torrent control engineering was introduced from European Alpine countries. The original technology has been improved by and by and adapted to the characteristics of Japanese natural and social situations. The improved works resulted in steady progress of erosion control effectivity in active torrents. As the result, the sediment yield from those torrents were reduced which mitigated the burden of downstream reaches.

The engineering standard of those works was almost fixed in the 1950's, but the people were confronted with another new problem. Namely, sediment disasters occur not only on existing devstated torrents but also on valleys which were believed to being dormant at the time. The works are effective for the recovery of the devastation but they can't prevent the disaster which happens at the initial event. The problem becomes a matter of public interest, not only because of the change of natural condition, but also due to the development of land-use and the change of socio-economical structure emphasizes the necessity of such kind of works.

It is a very hard problem requires careful considerations before responding, because the outbreak of such phenomenon is a stochastic process while the proper counter measures must be a deterministic one. Moreover, there are an enormous number of potentially unstable torrents. From this point of view, it is impossible to stand against every probable danger by constructing control facilities. We have to investigate comprehensive program to mitigate the disaster, including both engineering methods and emergency warning and evacuation system.

In order to confront this problem, the interdependence of sediment budget in each individual torrent and in a large scale watershed must be taken into account. Generally speaking, an extreme value as the stochastic process may be given principal importance for the former case, and an areal mean value moderated by synthetic process should be supposed for the later case. We have not enough information for clarifying this problem at the present, but a clue to the solution has begun to be understood.

3. Sediment budget in an individual torrent

The sediment disaster that occured in a small torrent was caused by debris-flows with scarce exception.

The factors affecting the magnitude of a debris-flow are numerous, such as topography, geology, climate, vegetation and so on. Perhaps we may adopt the muliple regression analysis for the reduction of a universal formula. However it may not be realistic because the contribution of each factor is different from case to case, and the magnitude of resulted debris-flow can be changeable within wide range even if the same conditions are given for all factors. Further, a debris-flow is supposed to occure merely at the extreme condition of a synthetic effect of those factors.

From these points of view, the correlations with some single factors are considered as the first step, regardless the effect of various related conditions. Aiming at the practical purpose, the total volume of a debris-flow discharge (volume of deposited materials), the drainage area of an individual torrent and the total volume of landslides in the area are taken into account. The data adopted are 551-examples occured from 1972 to 1977 which collected by the Ministry of Construction. The regression equations and the coefficients of correlation are as follows,

$$Vd = 13.6\ A^{0.61} \quad (c.c. = 0.52) \qquad Vs = 22.8\ A^{0.59} \quad (c.c. = 0.57) \qquad Vd = 0.914\ Vs^{0.838} \quad (c.c. = 0.84)$$

wnere, Vd ; total volume of debris-flow ($10^3 m^3$)
Vs ; total volume of landslides ($10^3 m^3$)
A ; drainage area of a torrent (km^2)

The distribution of data are shown in Fig.1(Vd-A relation) and Fig.2(Vd-Vs relation). Although the observed data are scattering widely around the regression equation, the pattern of distribution has a distinct character, namely the frequency of data can be approximated by the log-normal distribution. The pattern of frequency distribution corresponding to those three cases is shown in Fig.3. In the case of Vd-A and Vs-A relation the patterns are almost the same and the approximations are fairly good. Beside it the pattern for Vd-Vs correlation deviates a little more from the straight line. This character may be available for the estimation of a catastrophic event which has a low probability. The values estimated from this approximation corresponding to some given excessable probapilities are shown in following table.

excessable probability	1	5	10	20	30	50 (%)
Vd/R(A)	20.2	8.38	5.22	3.00	1.99	1.00
Vd/R(Vs)	10.9	5,41	3.73	2.44	1.77	1.00

The values R(A) and R(Vs)are representing the calculated values by the regression equations. Also, the lines corresponding to these probabilities are shown by broken-lines in Fig.1 and Fig.2.

As a matter of course, these two methods give different estimations. It is therefore necessary to check up the observed values Vd, Vs and A themselves, prior to the further considerations.

The patterns of frequency distribution relating to those

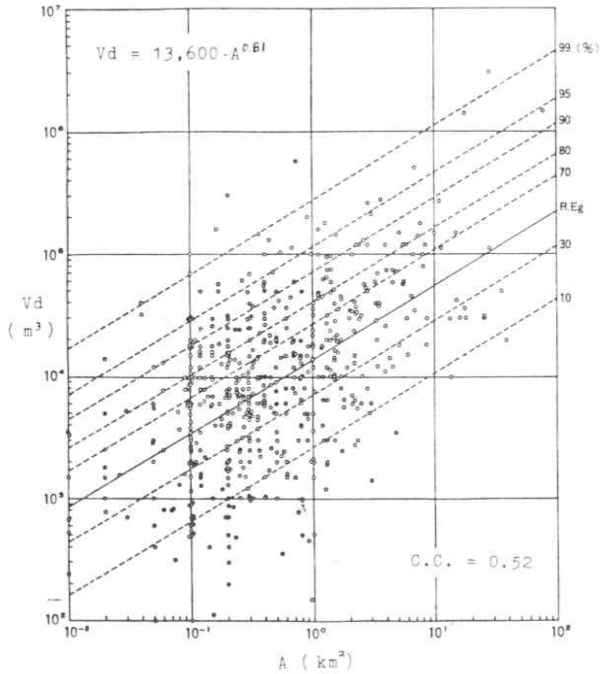


Fig. 1 Distribution of observed data relating to the Vd-A correlation

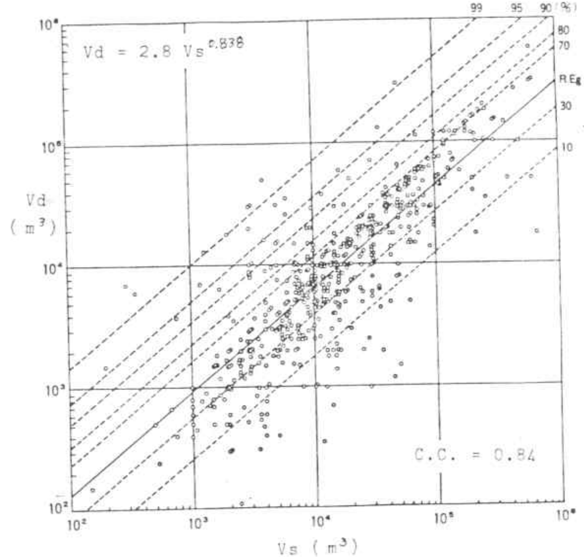


Fig. 2 Distribution of observed data relating to the Vd-Vs correlation

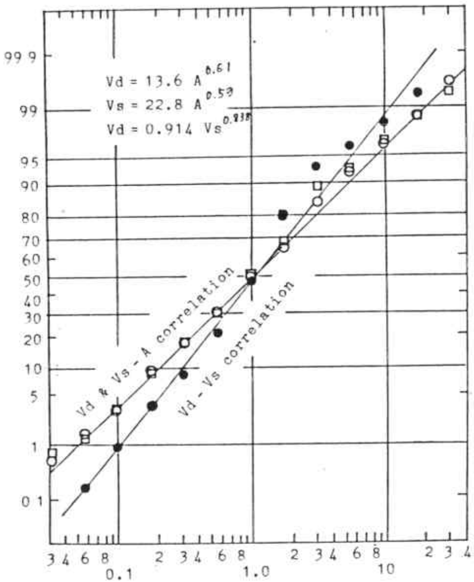


Fig. 3 Pattern of frequency distribution aroud the regression equations.

● : Vd-Vs correlation
○ : Vd-A correlation
□ : Vs-A correlation

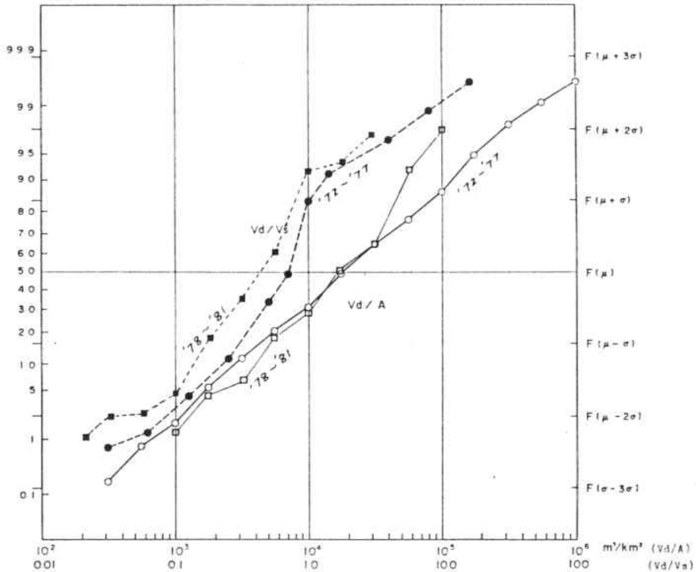


Fig.4 Frequency distribution of the values Vd/A and Vd/Vs. (1972-1977 and 1978-1981)

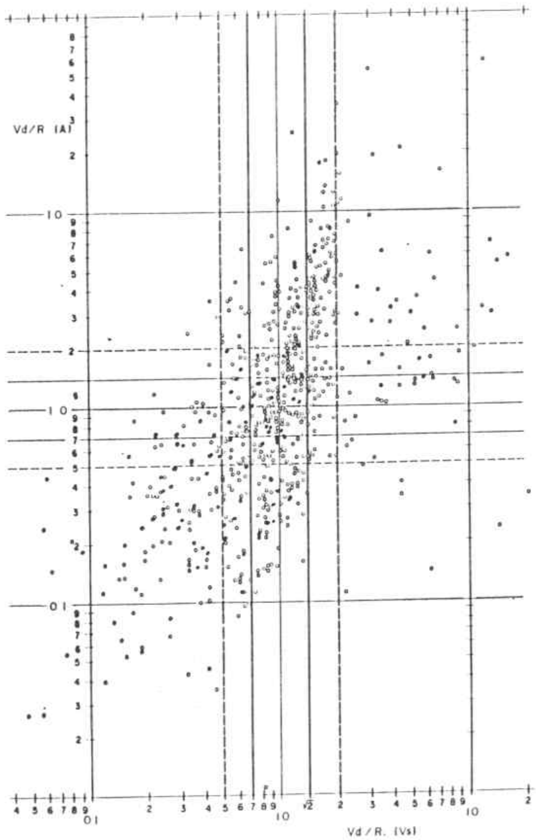
values can be approximated fairly well by means of the log-normal distribution for all cases. Therefore, they can be explained sufficiently by the mode (μ) and the standard deviation (σ). It may be more convenient for the explanation of log-normal distribution, if the ratio $S = F(\mu' + \sigma') / F(\mu') = F(\mu') / F(\mu' - \sigma')$ is used instead of the actual standard deviation. Herein, the apparent mean μ (= log μ') and the apparent standard deviation are used as the variable is transformed into logarithm, and the function F means the reverse transformation into the original values. Accordingly, the following values are reduced.

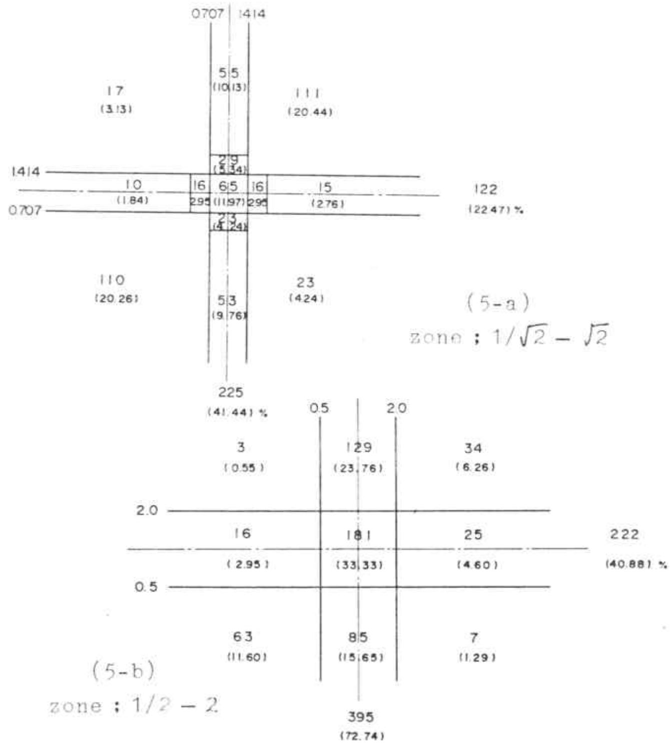
for drainage area A	μ = 0.56 km^2,	S = 4.38
for debris-flow volume Vd	μ = 8,600 m^3,	S = 4.77
for landslides volume Vs	σ = 14,000 m^3,	S = 4.47

Next check is the pattern of frequency distribution relating to the values Vd/Vs and Vd/A. That is, the former is the simplest index for the sediment budget and the later represents the degree of devastation in an individual torrent. The result is shown in Fig.4, and in this figure the data occued from 1978 to 1981 (93 examples) are shown together. The pattern of the Vd/Vs distribution shows an distinct S-shaped curve beside the Vd/A distribution which approximates a straight line on the log-normal probability paper. These tendencies are interpreted that the ratio of sediment discharge to sediment production is fluctuating between 0.3 and 1.0 generally and the frequency tends to increase as the ratio is increasing even though the possibility exceeding 1.0 is scarece, maybe less than 20 %, while the degree of devastation varis uniformly (in logarithmic scale) around the mode of distribution. The mode is about 20×10^3 cubic-meters so far as supposed from the experiences in Japan.

Although the difference between those two terms of record is not clear in shape, the values are a little smaller in the later one than the former though the number of data is far less in the later. Therefore the data in 1978-1981 are used for the inspection of the proposed method derived from the former data.

It must be necessary to settle the standard of possible volume of debris-flow for the establishment of practical mitigation system. For this purpose, the comparison between the observed data and the calculated values by means of the regression equations were attempted. The result is shown in Fig.5. In this figure, the ordinate and abscissa of each plotting point indicates the ratio Vd/R(A) and Vd/R(Vs) respectively. White circles are the data in 1972-1977, and black circles are those in 1978-1981. The plotting position of both circles distributes in almost the same way. The point included in the first quadrant means that the volume of debris-flow discharge is larger than both the standard volumes supposed from the Vd-A relation and Vd-Vs relation. On the contrary, the one in the third quadrant means the volume of debris-flow discharge is smaller than both those two values. In the second and fourth quadrants, the relations to Vd/A and Vd/Vs indicate the opposite combination. Almost all the data are distributed in the first and third quadrants or the neighbouring zone of them. Only a few data indicate





Numbers and percentages of data locating within neighbouring zones around regression equations.

Fig.5 Comparison between observed values and calculated values, by means of the plotted location on the co-ordinates of Vd/R(A) and Vd/R(Vs).

the distinct character of the second and fourth quadrant.

The regression equations for Vd-A and Vs-A correlation are expressed in proportion to the 0.61 and 0.59 power of A, and they may approximate to 0.6. As compared to the geomorphologic quantities, in the "Hack's Law" the length of the main channel is expressed in proportion to 0.6 power of A, and there is another report confirming this conception. Therefore, the values Vd and Vs may be regarded as the linear functions of main stream length as a rule. However, the sediment transport by a debris-flow may be controlled on account of the balance between the total runoff and sediment supply, and the fluctuation of the layer may be changeable in wide range, while the former may have a definite range of fluctuation. As the result, if the devastation of the mountain is so severe that it may mobilize too much materials, then the bed-materials may move together with the debris-flow. If it is not so severe, then a part of the whole drainage basin may contribute to the debris-flow. The general pattern of this tendency can be seen in Fig.5 as stated above, further it can be confirmed by means of the investigation of data distribution plotted separately by classified groups relating to Vs/A.

Fig.5-a and 5-b presents the numbers and percentages of data which are located within the range limited two-times and four-times centering around the calculated value by the regression equations, respectively. 22.47% and 40.88% are included in the case of A-based standard, 41.44% and 72.74% are in the Vs-based standard, and the case satisfied by both standards are about 1/8 and 1/4, corresponding to those two ranges. This general feature means that the discharge of the average debris-flow has a more close correlation with the volume of landslides in the source area than with the drainage area of torrent or the length of main torrent. The ranges within $(1/2\sim 2)\cdot R(Vs)$ and/or $R(A)$ can be regarded as the allowable limit for practical applications, considering the accuracy of the observed data. However, as the actual volume of landslides is not given before the occurence of the event, then this volume must be estimated by means of the other method. But it is easier than the direct estimation of debris-flow, because some methods were proposed already and those methods will be improved before long besides the accumulation of observed data are far more abundant in the case of landslides.

The relation between Vd-A and Vs-A correlation are suggesting other useful information. That is, as the powers 0.61 and 0.59 are almost the same for practical use, then the difference in the coefficient 22.8 and 13.7 means directly the difference between the sediment production and sediment yield in the case of debris-flow for an individual torrent. The ratio 0.40 (i.e. (22.8-13.6)/22.8) means that, about 40% of the collapsed materials is depositing in an unstable state within the torrent and in general the remaining 60% has been washed out of the torrent.

4. Sediment budget in a river-system

At first, it is necessary to define the scale of a total river-system, that is decided by the natural features of Japanese rivers and the historical aspect of the problem.

The rivers in Japan have relatively small watersheds and steep gradients, because the land consists of narrow and mountainous islands. Only four rivers have more than $10^4 km^2$ in drainage areas, and 50 rivers are more than $10^3 km^2$. The total area of these 50 rivers is about $206 \times 10^3 km^2$, that is about 55% of the whole country and almost the same as the total area of the mountainous region. These large rivers show the general tendency to be lower the river-bed in downstream reaches at the present, owing to the construction of reservoirs and the accomplishment of reforestation. As the result, the relative importance of sediment control in downstream areas is decreasing, and principal interest is turned to the problems relating to the inundation within middle and down-stream areas and the decrease of water storage capacity in reservoirs caused by sediment yield. Accordingly, the scale of a river-system as the objective of sediment control may be the watershed in which the highest stream-order does not exceed at least 2-order less than these large rivers, and the upper limit of the area may be about 100 to 500 km^2. The lower limit is considerd to be 5 to 10 km^2, because about 95% of whole debrisflows occured in the torrent having an area less than this value, according to the investigation described in the former section.

There are many research papers relating to the estimation of annual sediment yield from various watersheds in the world, and the major part of those works are based on the analysis of observed data of sedimentation in reservoirs and Sabo-dams. Many authers are adopting the multiple regression analysis for inducing the formulae to estimate the sediment yield. Factors used for the analysis are a watershed's area, annual or flood discharge, trap-efficiency of a dam, topography, geology, vegetation, degree of devastation and so on. However, the principal factors affecting this phenomenon are different from case to case, and the general tendency can hardly be found from this method, but a watershed's area A seems to be affecting directly or mediately whole cases. Accordingly, the formulae reduced to the simple correlation with A were examined at first. The formula may be written as follows,

$$q_d = K \cdot A^{-0.8} \quad (q_d\text{; annual sediment yield per unit area})$$

The most probable value for n is supposed to be around -0.8 for Japnese rivers. The value K varis within the range from 40 to 9.5×10^5, owing to the effect of whole remaining factors is compounded to this value. (Takahshi, 1971)

Fig.6 shows an example of the observed data relating to A-q_d correlation. The black circles are the data for Sabo-dams (the Ministry of Construction, 1966), and the white circles are for large reservoires (Ezaki, 1966). The total number of data is 60 and 29, those were checked and selected from the original data to be adopted for this purpose. The correlation between A and q_d is considered to be insignificant, because the data are scattering at random within a wide range. The envelopes of the data, adapting to the equation $q_d = K A^{-0.8}$, show the range of K of which the upper limit is 150×10^3 and the lower limit is 0.7×10^3.

Some regional characteristics may be recognized generally, but inconsistent data are found at the same time. The range of K is too wide for practical application, while it is constricted to a relatively narrow range as compared with the data covering all over Japan. The fact that the value n is almost -0.8 means that, the total volume of sediment yield Vd from a watershed is proportional to the 0.2-power of the area, also the volume Vd increases about 24% as the area A becomes 10-times larger. The fact seems to be the under-estimation of the effect of watershed area against our actual impression. Also, some attempts to use the multiple regression analysis seem to be suggesting that, it must be more realistic to examine the effect of the simplified hydraulic conditions exclusively. An example of such research was proposed by K.Ezaki(1966,'67), and he gave the following formulae.

$$Vd = 8.85 \cdot Qf \cdot Ir^2 + 7.83\, Qf \cdot (As / A) \cdot Is^2$$

$$\text{or} = 0.94\, Qf \cdot Ir + 1.33\, Qf \cdot (As / A)$$

where, Qf ; total amount of high-stage discharge q, which satisfys the condition $q \cdot Ir \geq 1.0$, that is large enough to move a stone having the diameter of about 15 - 90 mm.

Ir ; inclination of river-bed at the upstream end of reservoir

Is ; inclination of landslide surface (mean value)

As ; total area of landslides in the watershed

In these formulae, the first term corresponds to the discharge of bed-materials, and the second is wash-load respectively. It means that the sediment yield occurs mainly in the case of such high-stage discharge. These coefficients were induced from the observed data in 40 reservoirs and the formulae agree well with the observed data.

Consequently, it can be said that the sediment transport in middle reaches is controlled by the hydraulic equilibrium condition at the concerned section of river course. Also the source of suspended materials is the total area of landslides and bare-lands on mountainside slopes.

On the other hand, typical examples of significant disasters caused by heavy sediment yield in the past are indicating quite different feature on the sediment budget. This can be seen from Tani's report (1981), which compiles 27-examples of such events. Generally speaking, more than three-quarters of the matrials collapsed by landslides on mountainsides and slope-failures along streams were washed downstream in almost all cases.

Fig.7 shows the relation between the volume of sedimednt production per unit area (Vp/A) and the ratio of sediment yield and sediment production (Vd/Vp), wherein the data are classified into three groups by the relating area of watershed. The group shown by white circles are for the range $5\,km^2 \leq A < 10\,km^2$, where massive movement may affect considersbly to the sediment budget. Black circles are for the range of more than $40\,km^2$, where the tractive force and turbulence of running water may play a prin-

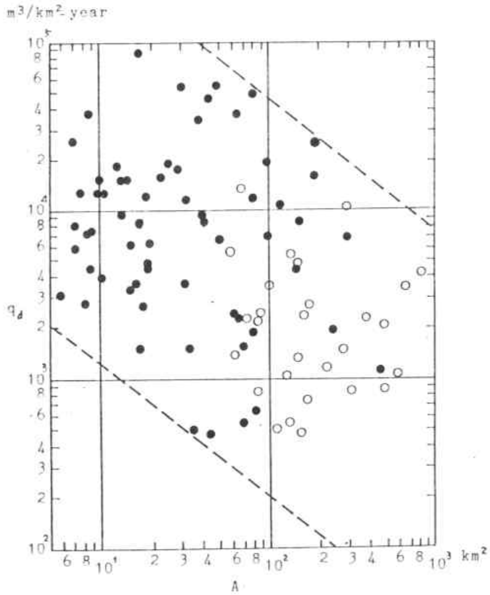


Fig. 6 Correlation between the annual sediment yield per unit area q_d and the relating watershed's area A.

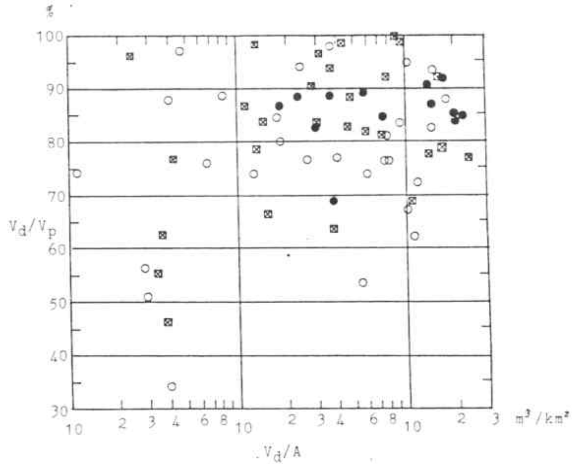


Fig. 7 Relation between the sediment production per unit area Vd/A and the ratio of sediment yield and sediment production Vd/Vp.

cipal part in sediment transport. Squares with crosshatching are for the intermediate and transitional range 10 km^2 ≤ A<40 km^2. The number of data in each group is 30, 17 and 29, respectively. For the calculation of those data, the values Vd were estimated by the balance between the total volume of collapsed materials and the transformation of river-bed materials surveyed before and after the disaster. Every datum shows a fairly large value for Vd/A as compared with the former cases, not only on sedimentation in dams but also on deposition by debris-flows. This tendency should not be neglected but be examined, even if there may be some question about the accuracy and reliability of those observed data.

The black circles are distributed within a narrow range centering around 85%, in all but one exception. These data were observed in a fairly high mountainous area with steep river-bed gradient where the mean scale of landslides was far larger than the other cases, and devastation activity of the area was rather dormant before the disaster. It can be interpreted that the landslides had dammed-up once the stream and the accumulated energy in the stored water grew large enough to sweep almost all materials out of middlestream reaches. The rainfall intensity was so heavy that the run-off water was stored in a short duration and the materials originate from landslides were mobilized through the sliding process. Perhaps almost all of those natural-dams were broken up during the duration of flood. This process can be testified to circumstantially by the remaining traces of natural-dams. In other words, such a severe disaster extending to wide areas may occur in certain restricted circumstances like these examples.

The other distinctive feature of Fig.7 is that the values Vd never exceed Vp, while about 10-15% of all data exceed Vs in the case of debris-flow. If the ratio Vd/Vs is adapted in place of Vd/Vp, ten data are exceeding 100% and all of them are in the case where the area A is less than around 10 km^2. Further, in three examples among the twenty-seven significant disasters, the typical mass-movement of bed-materials was recognized, wherein the volume of sediment yield was far larger than the volume of landslides. However, these data aren't included in this figure because the area A is less than 5 km^2 without exception. Among these 76 data, about one fifth of all exceed 90% in Vd/Vp ratio. It is supposed that the estimation of river-bed transformation tend to become larger than the actual value. Because scouring of fine bed-materials continues considerably after the disastrous event, also partial collapse of river course may be given more attention than local depositions. After due consideration of those uncertain factors, the following suggestions are given for the practical purposes.

The rivers in which debris-flows will be confluent directly to her main tributary, 75-90% of the total volume of sediment production should be expected to be the object of the sediment control planning. When the forecasted sediment production per unit area is less than around ten-thousands cubic meters, the ratio of sediment discharge may reduce to about a half of the former cases according to the general configuration of the area. In this case, it is more important to make a decision that the counter-measures be concentrated in some restricted localities, and that these dangerous area and proper counter-measures be found.

5. Conclusion

Sediment budget in an individual torrent and in a river system is quite different when the object of the estimation is aiming at their peculiar traditional problems. That is, the former was considered as the problem relating to the occurrence of a catastrophic event, while the later was treated as the long-term maintenance of a stable river course. From this point of view, it is reasonable to adapt the methodologies which were developed from their independent standpoints. However, these two problems are interrelated because there is a balance between the unstable materials in torrents and mountains and the yielded sediment by the transportation capacity of a river. Also these unstable materials are produced primarily by catastrophic events. Actually, such events occur at very long return periods and the materials produced in these cases seem to be transported to middle or down-stream reaches at almost the same time. The river morphology changes so slowly that it can be regarded as almost unchanging for our life-time, unless we happen to be caught in a catastrophic event.

Combining those two different factors, the transformation process in river course due to an exceptionally heavy supply of unstable materials is the conjuncting point of those two problems. The studies on this phenomenon are not completed at the present and further clarification of the problem is expected for a fundamental of watershed management.

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Adress of auther: Prof. Dr. A. Takei
Dept. of Forestry
Kyoto University
Kyoto 606 / Japan