

This invention relates generally to hydraulic shield tunnelling method and, more particularly, to an excavation controlling method in the hydraulic tunnelling with a shield type excavator.

5 In the hydraulic shield tunnelling, a slurry is fed as pressurized to a shield excavator going underground through a feeding pipe system from the exterior, mixed in the excavator with ground forming materials excavated at tunnel face (the materials shall be referred to hereinafter simply as "soil") including any soil collapsed from the tunnel face and discharged through a discharging pipe system to the exterior. The thus mixed and discharged slurry includes a solid component of the soil, which is settled and removed in a separating tank and remaining water is again fed as the slurry into the excavator through the feeding system. In practice, the slurry thus fed to the excavator through the feeding system still contains a certain amount of the solid component, and an electromagnetic flow meter and γ -ray densimeter are arranged in each of the feeding and discharging systems so that the amount of the solid component in the slurry fed through the feeding system and that in the mixed slurry discharged through the discharging system will be respectively detected through arithmetic operations and the substantial amount of the soil actually excavated and discharged out of the excavator will be thereby detected, as has been already suggested in, for example, U.S. Patent No. 4,040,666.

The actually excavated soil amount is generally determined by the advancing amount of the excavator and, in order to prevent any underground collapse at the tunnel face specifically in a soft and unstable ground, the excavator advancing amount or stroke must be rather precisely controlled in relation to the excavated soil amount. There has been also suggested in a Japanese Laid-Open Patent Application Publication

(15) No. 54-94725 of July 26, 1979 a controlling method of the excavator advancing amount in the hydraulic shield tunnelling, according to which signals denoting respective predetermined advancing strokes of the shield excavator are employed to drive
5 two recorders in synchronism with the excavator, the soil amounts excavated during such strokes are accumulatively recorded by a first one of the recorders, upper and lower control limit lines are thereafter added to a chart sheet of the first recorder on which the excavated soil amounts are recorded,
10 then the chart sheet is set in the other second recorder, further soil amounts excavated during subsequent advancing strokes are recorded on this chart sheet by the second recorder responsive to the advancing strokes, the excavator advance during the subsequent strokes is controlled so that
15 the excavated soil amounts will be within the two control limit lines during the subsequent strokes, and such recording and controlling are repeated for respective further advancing strokes. The thus detected amounts of the excavated soil are varying momentarily but are usually not greatly different
20 from a predetermined value and the excavation can be properly progresses. More specifically, with the progress of excavation for each predetermined distance, the detected amounts of the discharged soil (dry soil amount) are sampled to prepare a population, the mean value and standard deviation of this
25 population are calculated and a control limit is determined from these mean value and standard deviation. In other words, the excavator is stopped as being in "abnormal" state when a detected value different by more than a predetermined multiple of the standard deviation from the mean value is reached, so
30 that a proper measure can be taken for finding a cause for the abnormality and removing the cause.

According to this method, however, even a population based on the latest data of, for example, 100 samplings of

preceding excavations cannot be deemed to be the one representing exact state of the tunnel face accurately and faithfully. That is, even when the tunnel face or its vicinity has varied in practice to be comparatively soft and unstable as a whole, influences of the date for the preceding excavated positions are remained in the population being used at the moment and it is difficult to decide any variation in geologic nature and possible collapse of the ground at the tunnel face on the basis of such population.

According to the invention there is provided an excavation controlling method in hydraulic shield tunnelling wherein a slurry is fed to a shield type excavator through a feeding system from the exterior and a mixture of said slurry with soil excavated by said excavator is discharged out through a discharging system, said method comprising steps of

- (a) detecting solid component amounts contained in the fed slurry,
- (b) detecting solid component amounts contained in said mixture,
- (c) determining actually excavated soil amount from respective detected amounts of said solid components and sequentially storing said excavated amounts per unit excavation distance,
- (d) calculating the mean value and standard deviation of said excavated amounts per unit excavation distance,
- (e) deciding whether the excavated amount of the latest unit excavation distance is present in a deciding zone made by using said mean value and standard deviation, and
- (f) stopping the excavator when it is decided in said step (e) that the said excavated amount is not present in said deciding zone.

By way of example, preferred embodiments of the

invention will now be described with reference to the accompanying drawings, in which:

FIGURE 1 is a fragmentary block diagram of an electric information system of a hydraulic shield tunnelling method to which the present invention is applied;

FIG. 2 is an explanatory diagram of a macroscopic sampling treatment of the present invention;

FIG. 3 is an explanatory diagram of a microscopic sampling treatment of the present invention.

While the present invention shall be explained in the followings with reference to the preferred embodiments, the intention is not to limit the invention to the particular embodiments but rather to include all alteration, modifications and equivalent arrangements possible within the technical scope of appended claims.

Referring now to FIG. 1, a pipe 1 forming a feeding system for feeding a slurry to an excavator from the exterior is provided with an electromagnetic flow meter 2 and γ -ray densimeter 3, and a pipe 4 forming a discharging system for discharging a mixture of the slurry with excavated soil from the excavator to the exterior is also provided with an electromagnetic flow meter 5 and γ -ray densimeter 6. An arithmetic memory circuit 7 is connected to the respective

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meters 2,3 and 5,6 for calculating the amount of fed solid
 component contained in the slurry and fed to the excavator
 according to detected signals of the flow meter 2 and densimeter
 3 in the feeding system and the amount of discharged solid
 5 component contained in the mixture discharged out of the
 excavator according to detected signals of the flow meter 5
 and densimeter 6 in the discharging system, computing the
 substantial excavated soil amount of the excavator depending
 on the difference between the two calculated amounts and storing
 10 this excavated soil amount. A detector 8 detects protruded
 plunger stroke length of a jack for advancing the excavator
 and provides its detected signals to the arithmetic memory
 circuit 7, and an indicating circuit 9 properly indicates stored
 contents in the arithmetic memory circuit 7 and is artificially
 15 prepared for macroscopic and microscopic sampling treatments.

The arithmetic memory circuit 7 stores the
 substantial excavated soil amount calculated on the basis of
 signals from the detector 8 whenever the excavator advances by
 2.5 cm, that is, whenever the plunger stroke length of the jack
 20 reaches 2.5 cm. Usually, whenever the jack stroke length reaches
 100 cm, the reinforcing segment is installed at the rear end
 of the excavator, the jack fixing position is advanced and then
 the excavator is again advanced by the jack. The arithmetic
 memory circuit 7 adds the stored excavated soil amounts for
 25 every interval of 2.5 cm and stores them as excavated soil
 amount per segment (a segment excavation amount X_i). At every
 time when each segment excavation amount X_i is obtained, a mean
 value $\bar{X}$ and standard deviation σ will be calculated. When a
 newly arriving segment excavation amount X_{i+1} meets any one of the
 30 following conditions, it will not be included in the population
 including the segment excavation amount X_i , that is, it will be
 included in a population different from the particular
 population including the segment excavation amount X_i , the

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excavator will be artificially or automatically stopped, the cause will be searched and necessary measures will be taken.

Deciding Condition I:

- When $|X_i - \bar{X}| > 2\sigma$ and $|X_{i+1} - \bar{X}| > 2\sigma$,
5 then X_{i+1} belongs to a different population.

Deciding Condition II:

- When $X_{i-4} - \bar{X} > 0, X_{i-3} - \bar{X} > 0,$
 $X_{i-2} - \bar{X} > 0, X_{i-1} - \bar{X} > 0, X_i - \bar{X} > 0$ and $X_{i+1} - \bar{X} > 0$ or
10 $X_{i-4} - \bar{X} < 0, X_{i-3} - \bar{X} < 0, X_{i-2} - \bar{X} < 0,$
 $X_{i-1} - \bar{X} < 0, X_i - \bar{X} < 0$ and $X_{i+1} - \bar{X} < 0,$
then X_{i+1} belongs to a different population.

Deciding Condition III:

- When $\bar{X} + \sigma \leq X_{i-1}, X_i, X_{i+1} \leq \bar{X} + 2\sigma$ or
 $\bar{X} - 2\sigma \leq X_{i-1}$ and $X_i, X_{i+1} \leq \bar{X} - \sigma$, then X_{i+1} belongs to a
15 different population.

Deciding Condition IV:

- When $X_{i-4} - X_{i-5} > 0, X_{i-3} - X_{i-4} > 0,$
 $X_{i-2} - X_{i-3} > 0, X_{i-1} - X_{i-2} > 0, X_i - X_{i-1} > 0,$ and
 $X_{i+1} - X_i > 0$ or
20 $X_{i-4} - X_{i-5} < 0, X_{i-3} - X_{i-4} < 0, X_{i-2} - X_{i-3} < 0,$
 $X_{i-1} - X_{i-2} < 0, X_i - X_{i-1} < 0$ and $X_{i+1} - X_i < 0$, then
 X_{i+1} belongs to a different population.

Deciding Condition V:

- When $\bar{X} - 2\sigma \leq X_{i-2}, X_{i-1}, X_i, X_{i+1} \leq \bar{X} - \sigma$ or
25 $\bar{X} + \sigma \leq X_{i-2}, X_{i-1}, X_i, X_{i+1} \leq \bar{X} + 2\sigma$, then
 X_{i+1} belongs to a different population.

Deciding Condition VI:

- When $R = |X_i - X_{i+1}| > 2.83\sigma$, then X_{i+1} belongs
to a different population.

- 30 It will be clear that, at the time of starting the
excavation, the segment excavation amount X_i is not known yet
and, therefore, the segment excavation amount X_s and standard
deviation σ_s are to be properly set by the measuring precision

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of the electromagnetic flow meters 2 and 5, γ -ray densimeters 3 and 6 and detector 8, the excavating velocity of the excavator and the geological conditions.

FIG. 2 is a diagram showing the foregoing deciding operation of the controlling method according to the present invention as indicated by the indicating circuit 9, or that operation performed within the arithmetic memory circuit 7. It should be here assumed that, at a stage where the calculations are made up to a segment excavation amount X_{112} corresponding to the 112th reinforcing segment, this segment excavation amount X_{112} is found to belong to the same population as of the respective preceding segment excavation amounts X_{100} to X_{111} . The mean value $\overline{X_{100-112}}$ and standard deviation $\sigma_{100-112}$ for the segment excavation amounts $X_{100} - X_{112}$ are calculated and the upper control limit $\overline{X_{100-112}} + 2\sigma_{100-112}$ and lower control limit $\overline{X_{100-112}} - 2\sigma_{100-112}$ are illustrated respectively in the diagram with broken lines. Even in a state where a further segment excavation amount X_{113} corresponding to the 113th segment is calculated, too, the same arithmetic operation is carried out. As will be clear when the deciding condition I is considered in a state where a segment excavation amount X_{114} corresponding to the 114th segment is calculated, the respective segment excavation amounts X_{113} and X_{114} will fall under this condition I and, therefore, the amount X_{114} will be decided to belong to a different population. In accordance with this, the excavator will be stopped, and any cause for the abnormality will be search and removed for continuing the subsequent operations. While FIG. 2 shows the further results of continued excavating and deciding operations, they will be almost self-evident from the foregoing descriptions and their explanations shall be omitted, but it should be simply noted that as the respective segment excavation amounts X_{100} to X_{112} , X_{113} to X_{127} and X_{128} to X_{132} are shown as forming respectively different populations, decision making zones

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derived from the mean values and standard deviations of the
respective populations will vary in such manner as illustrated.

Not only the above described "20 method" but also the
following "analysis of variance by one-way layout" can be
5 adopted in the controlling method of the present invention.
For the purpose of simplicity, the explanation shall be made
by using the segment excavation amounts plotted in FIG. 2.

When the segment excavation amount X_{113} is calculated,
the respective amounts are divided into a first segment
10 excavation amount group consisting of the already calculated
amounts X_{109} , X_{110} and X_{111} and a second segment excavation
amount group consisting of the other amounts X_{112} and X_{113} ,
and the both groups are respectively analyzed by the "analysis
of variance by one-way layout" and compared with each other
15 so that the uniformity of the both groups will be obtained,
according to which the excavation will be made for the next
segment length and a segment excavation amount X_{114} is calculated.
At this time, too, the division into a first group consisting
of the segment excavation amounts X_{110} , X_{111} and X_{112} and a
20 second group consisting of the segment excavated amounts X_{113}
and X_{114} , the "analysis of variance by one-way layout" of these
groups and their comparison are performed, and their uniformity
will be denied as seen in the drawing. At this time, the
excavator will be stopped and the cause will be found and, only
25 when nothing is abnormal, the excavation will be advanced in the
same manner as has been described in the foregoings.

By the foregoing descriptions, the macroscopic
sampling treatment of the present invention can be carried out.

In addition, in the present invention, the microscopic
30 sampling treatment is made for each segment to accelerate the
controlling operation and to simplify and economize the
controlling device.

The microscopic sampling treatment is made by deciding

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whether, the, before described excavated amounts stored in the arithmetic memory circuit 7 at every excavator advance by 2.5 cm, that is, at every protrusion by 2.5 cm of the jack plunger are present in a desired range or not. For simplifying the following explanation, symbols shall be attached to these excavated amounts. The part corresponding to Nth segment is now being excavated, "i"th excavated amount of every 2.5 cm excavation is expressed as $(NX)_i$ and the excavated amounts $(NX)_k$ up to (N-1)th segment are grouped by noting "k". Statistics are taken among the excavated amounts $(NX)_k$ in which "k" is the same and the mean value $\overline{[(N-1)X]}_k$ and standard variance $\sigma_{(N-1)2K}$ are determined.

$$\frac{\overline{[(N-1)X]}_k \pm 2 \sigma_{(N-1)2K}}{\overline{[(N-1)X]}_k} \equiv A_{\pm}$$

is plotted in the indicating circuit 9 as in FIG. 3 or is stored in the arithmetic memory circuit 7. Then, $(NX)_i / \overline{[(N-1)X]}_k$ is indicated by the indicating circuit 9 as shown in FIG. 3 and whether

$$A_- \leq (NX)_i / \overline{[(N-1)X]}_k \leq A_+$$

holds or not is decided by sight. It will be clear that this decision may be of course made in the arithmetic memory circuit 7. If the above decision formula is satisfied, — it is satisfied at every point in the case of FIG. 3 — the excavation will be continued. If it is not satisfied, the excavator will be stopped, the cause will be searched and proper measures will be taken.

At the time of starting the excavation, the excavated amount and standard deviation shall be properly set in advance in the same manner as in the foregoing macroscopic sampling treatment.

In determining the cause for the abnormality on the basis of the macroscopic and microscopic sampling treatments

for the control method according to the present invention, fluctuation pattern and the like of the thus theoretically calculated values due to ground layer variations and ground collapses are considered as will be evident to the skilled
5 in the art and its explanation shall be omitted.

An advantage of these embodiments of the present invention is that an excavation controlling method in hydraulic shield tunnelling is provided which allows to decide a proper control limit which faithfully representing
10 any minute geologic variation in the tunnel face ground with the progress of tunnel excavation by means of the shield excavator, so as to render the safety of the tunnelling to be higher.

A further advantage of these embodiments is that a
15 method for controlling hydraulic tunnelling with shield excavator is provided wherein an excavated soil amount discharged from the excavator is subjected to a sampling for each of predetermined advanced distances of the excavator, the distance corresponding to the width of
20 respective tunnel wall reinforcing segments installed behind the excavator as the same is advanced, and decisions are made sequentially whether or not each sampling value of the latest obtained soil amount belongs to the same population as that of a preceding sampling
25 value for a preceding advanced distance and the excavation control is performed in response to results of such decisions.

A still further advantage of the embodiments of the present invention is that a hydraulic shield tunnelling
30 excavation controlling method is provided which is performed by deciding whether or not the sampling values sampled with respect to respective advanced distances of the excavator for the respective tunnel wall reinforcing segments are belonging to a population including
35 immediately preceding sampling values by means of the "2σ

method".

Another advantage of these embodiments of the present invention is that an excavation controlling method for the hydraulic shield tunnelling is provided which is performed by setting two sampling groups of excavated soil amounts respectively sampled for each of repetitive excavator advances by a predetermined distance, one of which group including the latest sampling value of the just excavated soil amount, and deciding whether or not these two sampling groups are merely two divisions of sampling values belonging substantially to the same population by means of an "analysis of variance by one-way layout", that is, whether or not the latest sampling value shows an abnormal state of the tunnel face.

A further advantage of the embodiments of the present invention is that a method is provided of controlling hydraulic shield tunnelling excavation for safely performing the tunnelling by sampling the respective discharged soil amounts per a fixed interval such as 2.5 cm for each tunnel-wall-reinforcing segment length in tunnelling direction such as 100 cm, forming a population with sampling values at respective sampling positions in the respective segment lengths and deciding whether or not sampling values at respective sampling positions of a new segment belong to the population by means of the "2σ method".

A still further advantage of these embodiments of the present invention is to provide a method for precisely controlling the hydraulic shield tunnelling excavation wherein a macroscopic sampling treatment is made at intervals corresponding to the segment length, any macroscopic geological variation in the tunnel face ground is detected, a microscopic sampling treatment is made at the same time at minute intervals for each segment length and any microscopic geological variation representing any quick variation such

as a collapse of the ground is detected.

A yet further advantage of the embodiments of the present invention is that a quickly and automatically performable tunnel excavation control method is provided
5 by dividing the sampling treatments into macroscopic and microscopic treatments so as to reduce any load due to the sampling treatment and to enable it possible to employ comparatively inexpensive computing devices.



CLAIMS:

1. An excavation controlling method in hydraulic shield tunnelling wherein a slurry is fed to a shield type excavator through a feeding system from the exterior and a mixture of said slurry with soil excavated by said excavator is discharged out through a discharging system, said method comprising steps of
 - (a) detecting solid component amounts contained in the fed slurry,
 - 10 (b) detecting solid component amounts contained in said mixture,
 - (c) determining actually excavated soil amount from respective detected amounts of said solid components and sequentially storing said excavated amounts per unit excavation distance,
 - 15 (d) calculating the mean value and standard deviation of said excavated amounts per unit excavation distance,
 - (e) deciding whether the excavated amount of the latest unit excavation distance is present in a deciding zone made by using said mean value and standard deviation, and
 - 20 (f) stopping the excavator when it is decided in said step (e) that the said excavated amount is not present in said deciding zone.
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2. An excavation controlling method according to Claim 1 wherein said deciding zone is expressed as $(\bar{X} - 2\sigma, \bar{X} + 2\sigma)$ by said mean value $\bar{X}$ and standard deviation σ of a population including said excavated amount of an immediately preceding unit excavation distance.
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3. An excavation controlling method according to Claim 1 wherein said deciding zone is determined by said mean value and standard deviation of a first group of said excavated amounts of a plurality of said unit excavation
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- distances preceding and continued to an immediately preceding unit excavation distance and thus excluding the excavated amount of said immediately preceding unit excavation distance, these mean value and standard of said first group is compared with the mean value and standard deviation of a second group of the excavated amounts of the latest and immediately preceding unit excavation distances, and whether the respective excavated amounts of said two groups belong to the same population.
4. An excavation controlling method according to Claim 1 wherein said steps (a) to (c) are performed by determining and sequentially storing said excavated amounts of minute unit excavation distances dividing said unit excavation distance,
- said step (d) is performed by calculating said mean value and standard deviation of the excavated amounts of said minute unit excavation distances of the same dividing order, and
- said step (e) is performed by deciding whether the excavated amounts of the minute unit excavation distances of the same dividing order of the latest unit excavation distance are present in said deciding zone made by said mean value and standard deviation.
5. An excavation controlling method according to Claim 4 wherein said deciding zone is expressed as $(\bar{Y} - 2\sigma, \bar{Y} + 2\sigma)$ by said mean value $\bar{Y}$ and standard deviation σ of said excavated amounts of said minute unit excavated distances of the same dividing order.
6. An excavation controlling method substantially as herein described with reference to and as illustrated by Figure 1 and Figures 2 or 3 of the accompanying drawings.

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