RESEARCH PAPER

TESTING BED LOAD TRANSPORT FORMULAS: A CASE STUDY OF THE LOWER AMUR BASED ON MULTI-BEAM ECHO-SOUNDERS (MBES) DATA

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ABSTRACT. The development of bed load calculation methods directly depends on the reliability of the measurement data. The most reliable measurement data remains the data obtained by the volumetric method when observing the filling of reservoirs, borrows, ditches etc. Nevertheless these data are the rarest. In this paper on the base of the data obtained when observing the process of filling of a ditch across the Amur River a comparison of a number of bed load calculation methods is performed. The observations were carried out with a multi-beam echo-sounder during summer floods of 2018, from 21st of July to 22nd of August. Over this time 5 surveys were performed, that allows to have 4 calculation periods for determining bed load yield. The total number of the measurements at different calculation verticals is 108. These data are used for verification of 80 bed load formulas. Four methodological approaches are considered: bed form approach, critical velocity approach, critical water discharge approach and regression approach. The bed form approach has shown the greatest accuracy: 17 formulas out of 26 gave the error less than 60%. For the other 56 methods which were considered only 5 formulas showed the error less than 60%, all of them correspond to the critical velocity approach.

KEYWORDS: bed load measurement, transverse ditch filling, bed load formula, bed load sediments, sediment transport, Amur

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INTRODUCTION

Bed load transport is difficult to measure. Despite the active development and improvement of the alternative measurement methods bed load traps remain a widely used means of bed load measurement. The first traps appeared at the beginning of the 20th century, and a large number of their designs were proposed later. In 1954, basing on the analyses of the experience in the creation and use of bed load traps accumulated by that time, Shamov (1954) formulated the following conclusions:

• Bed load traps of all designs introduced into the flow radically change the natural structure of the flow, the channel morphology at the places of their installation and the mode of bed load transport.

• All the traps have some design disadvantages that as a rule do not provide a tight coupling of a trap with a bed, taking into account irregularities of river bed and presence of bed forms or cobbles. As a result the bed is washed out in front of the trap inlet, and the natural regime of bed load transport and conditions of sediment entry into the trap are violated.

• In flowing water at considerable depths, with flow velocities of more than 2-3 m/s and intensive bed load transport it is difficult to lower and install the trap on the bed. It drifts with the current.

• When using traps with a mesh bag, the size of the mesh cells affects the trap readings.

Other disadvantages were also mentioned. General conclusion made by Shamov is that "all bed load traps do not satisfy the main requirement that is imposed on them: reliability and accuracy for accounting of bed load".

After Shamov's (1954) generalization the activity of creating new designs of traps was limited in the USSR and there was a reorientation to the search of alternative measurement methods as for the conditions of lowland and mountain rivers.

In other countries the search of more advanced designs of the traps continued, but today we can state that none of Shamov's critical conclusions have been refuted or resolved by these studies.

In the 1960s studies of bed forms intensified and a method of measuring bed load in plain rivers via dunes characteristics progressed. This method was most actively developed in the USSR, where in the period of the 1960-1980s a significant number of measurements were carried out in large, medium and small plain rivers (Snischenko 1966; Korchokha 1968; Kulyomina 1968; Kapitonov et al. 1974; Bashkov et al. 1991). In the USSR and Russia the method is called "iterated lengthwise echo-sounding" (ILES), in English-language literature it is referred to as "bed form velocimetry method".

With the emergence of multi-beam echo-sounders (MBES) this method received a new impulse to development. Baranya and Muste (Muste et al. 2016; Kim et al. 2016) have developed the AMV-method (acoustic mapping velocimetry) that allows to get bed forms characteristics across the width of the river covered by echo-sounder. Abraham with colleagues (Abraham et al. 2015; Baranya et al. 2016; Abraham et al. 2018) have developed the ISSDOT-method (integrated section surface difference over time) which calculates bed load by comparing three-dimensional bed surfaces over consecutive timelines of echo-sounding bypassing the determination of height and velocity of dunes and operating directly with the volume of degradation/aggradation between the surveys.

Despite the prospects of measuring bed load by echo-sounders, the most reliable measurement data remains the data obtained by the volumetric method when observing the filling of reservoirs, borrows, ditches etc. Nevertheless these data are the rarest.

The development of bed load calculation methods directly depends on the reliability of the measurement data. Contrary to the imperfection of the bed load measurement method by traps, these data (along with laboratory data) most often serve as the basis for comparison and derivation of bed load formulas (Kiat et al. 2007; Bombar et al. 2010; Talukdar et al. 2012; Sirdari et al. 2014).

In 2011-2015 the State Hydrological Institute (SHI) carried out studies in which effectiveness of bed load formulas for large rivers was evaluated based on the data obtained by the iterated lengthwise echo-sounding method (Samokhvalova 2011; 2012; 2013; 2014; 2015a; 2015b).

In this paper a comparison of bed load calculation methods is performed on the base of the data obtained by the volumetric method when observing the process of filling of a ditch across the Amur River. The process of the ditch filling was monitored using MBES.

MATERIALS AND METHODS

The source data for this work were obtained during the construction of the reserve line of the Eastern Siberia – Pacific Ocean oil pipeline (ESPO-2) that crosses the Amur River.

This river crossing is located on the Lower Amur, 34 km lower Khabarovsk (Fig. 1). The width of the river in the crossing line at the design water level of 31.5 m of Baltic System of Heights (BS) is 2485 m, mean depth is 6.9 m, maximum depth is 15.9 m.

The Amur flows in the area of monsoon climate and is characterized by high water content during the all warm period of year and low water in winter. In winter the surface of the river is covered by ice. Snow-melt flood begins in March, reaches its peak in May and at the beginning of July rain floods start. In Fig. 2 there is a hydrograph of the Amur near Khabarovsk. Rain floods usually pass from July to September. There are about 3-5 rain floods on average. The highest water levels are observed in this period.

Such long and high floods combined with relatively fine sediments cause a high intensity of bed load transport during the warm period of year. At the considered reach the channel is braided and has a low and wide floodplain with plenty of branches and lakes (Fig. 3). During flooding of the floodplain the finest particles of suspended sediments settle on the floodplain and contribute to stability of many islands in a long-term period. Bed load transport in the river occurs in the form of bars. It causes significant vertical deformations of the channel. In particular from 1941 to 2008 the magnitude of fluctuation of bed elevation was 12 m.

All these circumstances make the pipe-laying by the channel-buried method undesirable. The directional drilling method would be more desirable, but due to the

Fig. 1. The ESPO-2 crossing through the Amur

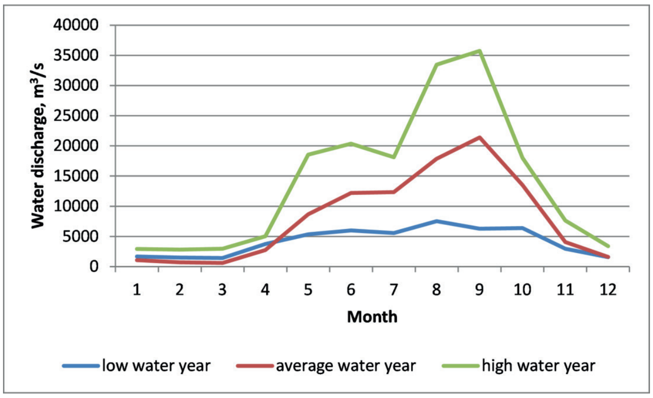

Fig. 2. Hydrograph of the Amur near Khabarovsk

Fig. 3. The ESPO-2 crossing through the Amur on the satellite image

large width of the river it couldn't be implemented. That is why the channel-buried method was chosen.

Due to the fact that in the low water period the surface of the river is covered with ice, the construction works were carried out in the high water period.

In summer 2018 the ditch digging started, but soon the work had to be paused due to high water levels and intensive bed load transport. This circumstance was used for observing of the ditch filling. The observation was carried out in the period from 21st of July to 22nd of August.

The measurements of the ditch filling were carried out by MBES SeaBat T20-R (number of beams 10-1024, swath coverage 165°, depth resolution 6 mm, teledyne INS (heading) 0.015°, teledyne INS (true heave) 2 sm). 5 echo surveys were performed in total: 21st and 27th of July, 1st, 7th and 22nd of August, 2018. Riverbed profiles were plotted for every calculation section of the ditch for each date (Fig. 4).

According to the governing document of the State Hydrological Institute that regulates accounting for channel deformations in construction of pipeline crossings across rivers[1], when width of ditch is significantly larger than length of eddy zone, volume of suspended sediments in total volume of sediments deposited in the ditch is 3-10%. Due to the large width of the Amur River the trenching was stretched out in time, and timelines of the ditch completion were different at different sites. The echo-sounding was carried out on certain dates, so the available profiles register intermediate states of the ditch. In view of the absence of the ditch profiles fixing its configuration before the beginning of irreversible filling to apply the recommendation of the SHI Standard for evaluation of the part of suspended sediments in the aggradation formed during the calculation period is problematic. There is also no data on suspended load at the study reach of the river for the period of trenching. However due to the fact that the ditch filling occurred in the period of floods, and flow velocities were quite high, and mean concentration of suspended load near Khabarovsk is pretty low and equals 90 g/m^3 (Makhinova et al. 2018), in this work we assume that the ditch was filled only by bed load. The area of aggradation formed between the adjacent echo surveys was assumed to be equal to bed load yield for this period.

Bed load yield measurements were performed for 4 periods (Table 1). The total number of the measurements at different verticals over this time is 108, the total number of the verticals is 32. The location of the measurement verticals is shown in Fig. 5.

These data have been used for verification of bed load formulas. In this work we have tested only a part of methodological approaches, in particular

- bed form approach ($q_b=f(h_D,C_D)$), where h_D – dune height, m, C_D – dune velocity, m/s),
- critical velocity approach ($q_b=f(V_0)$),
- critical water discharge approach ($q_b=f(q_0)$),
- regression approach.

In the first case different combinations of formulas for height and velocity of dunes are considered and calculations are performed using a general formula $q_b=0.6h_DC_D$, where q_b – bed load discharge in bulk volume, m^3/(s·m), 0.6 – dune form coefficient.

80 bed load formulas and their modifications have been tested in total, 26 of them are based on the first methodological approach.

Calculations of bed load discharge and yield have been performed for the verticals of the ditch line for which we have aggradation profiles for the considered period.

Flow characteristics required for the calculations have been taken from a gauge located 120 m upstream from the ditch line. On the 2nd of August there were performed measurements of velocity and depth of flow.

During the all period from 21st of July to 22nd of August water level measurements were being carried out at the gauge section (Fig. 6). Values of flow velocity V for every water level are calculated by the Chezy formula $V=C\sqrt{HI}$, where C – the Chezy coefficient, H – depth of flow, m,

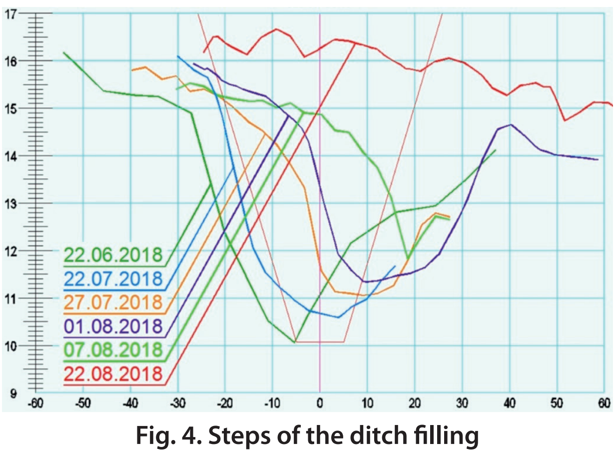

Fig. 4. Steps of the ditch filling

Fig. 5. Location of the measurement verticals

Table 1. Timing and number of bed load yield measurements

Period	Number of days	Number of verticals
from 21st to 27th of July	6	27
from 27th of July to 1st of August	5	28
from 1st to 7th of August	6	31
from 7th to 22nd of August	15	22

[1]Accounting for channel process at river crossings of pipelines: STO SI SHI 08.29-2009, 2009, 175 p.

I – slope, $C=\frac{1}{n}H^{\frac{1}{6}}$, n – roughness coefficient. Roughness coefficients are taken constant for every vertical. Slope is also assumed to be constant and equal to 0.000064. The calculated values of hydraulic characteristics vary within the following limits: 2.58≤H≤16.53 m, 0.49≤V1.48 m/s, the Froude number $0.08 \le Fr = \frac{V}{\sqrt{gH}} \le 0.17$,

where g – gravitational acceleration, m/s^2.

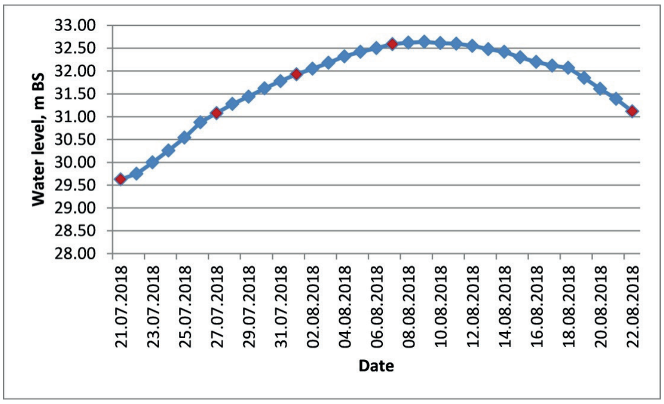

Fig. 6. Graph of water level for the period from 21st of July to 22nd of August (the dates of echo-sounding are highlighted in red)

During these measurements bed sediments were not sampled, but on the other hand an extensive geological examination was performed. As a result of this survey 3 homogeneous geological complexes (HGC) were identified on the river bed. For these complexes averaged particle size distribution curves were calculated. We compared these 3 curves with the curves of bed sediments sampled on this site in 2016 and they appeared to be close (Fig. 7). That is why for our calculations we use these 3 averaged curves. The main parameters of the particle size distribution curves are given in Table 2.

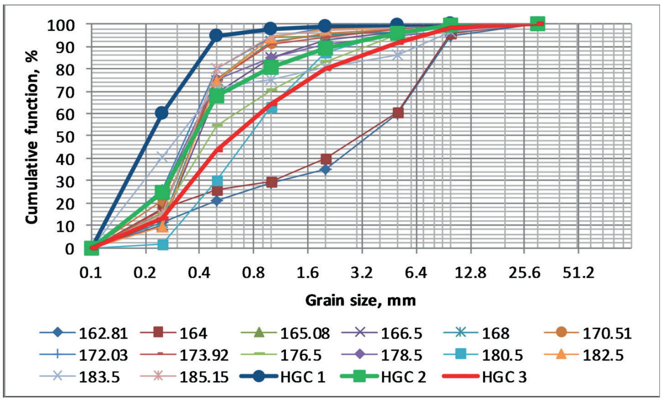

Fig. 7. Particle size distribution curves of bed sediments at different verticals in the crossing line (according to 2016 data) in comparison with the distribution curves of the homogeneous geological complexes identified on the river bed

Flow depth, flow velocity and corresponding bed load discharge in m^3/s/m (by each of the analyzed formulas) are calculated for each average daily level. The resulting bed load discharge is multiplied by the number of seconds in a day (86400) and thus bed load yield per day is obtained. The sum of daily bed load yield values for the considered period is compared with the corresponding value of aggradation. Calculation error is evaluated by the formula

$$\Delta = \frac{\left|Q_{b_{calc}} - Q_{b_{meas}}\right|}{Q_{b_{meas}}} 100\,\%$$

where $Q_{b_{calc}}$ and $Q_{b_{meas}}$ – calculated and measured bed load yield accordingly.

RESULTS AND DISCUSSION

Bed form approach has shown the best result: out of 26 formulas 13 have given the error lower than 50% and 4 more formulas the error less than 60%. Out of 54 other considered methods only 5 formulas have given the error lower than 60%, all of them belong to the critical velocity approach. Expressions of the dune height and velocity formulas which in combination with each other have shown best results are given in tables 3-4. Table 5 contains expressions other bed load formulas (not taking into account dune characteristics) with best results. Table 6 shows mean calculation errors of these formulas. Almost all the formulas except certain specified cases use critical (permissible) velocity V_0, m/s, by V.N. Goncharov (1938)

$$V_0 = 0.96\sqrt{g}H^{0.2}(d+0.0014)^{0.3} \qquad (1)$$

Formulas 1-7, 9-11 and 21 have confirmed their effectiveness for large plain rivers identified earlier in studies based on the data obtained by the iterated lengthwise echo-sounding method (Samokhvalova 2012; 2014; 2015a; 2015b). In those studies the total number of bed load measurements was 105, and main hydraulic characteristics of the large rivers varied as follows: 2.90≤H≤13.7 m, 0.72≤V≤2.1 m/s, Fr<0.2, 0.3≤d≤2.9 mm. From the comparison of these hydraulic characteristics with the hydraulic characteristics of the data used in this work it follows that they are very close. Consequently formulas 1-7, 9-11 and 21 can be recommended with greater confidence for bed load calculations in large rivers in the described range of the main hydraulic characteristics. And the circumstance that approximately the same formulas give good results for the both measurement methods implicitly indicates, among other points, the effectiveness of measuring bed load by the ILES method.

CONCLUSION

During the construction of the reserve line of the ESPO-2 oil pipeline across the Amur unique data on bed load transport in a large river were obtained by monitoring the process of the natural ditch filling by MBES.

Table 2. The main parameters of the particle size distribution curves of the homogeneous geological complexes identified on the river bed in the crossing line

Sample	d, mm	d_{50}, mm	d_{90}, mm
HGC 1	0.35	0.25	0.45
HGC 2	1.1	0.40	2.3
HGC 3	1.8	0.65	4.6

Note: d – weighted average diameter, d_{50} – median diameter, d_{90} – particle size for which 90% of the sample is finer.

Table 3. Dune height (h_D, *m*) formulas that showed the least error in bed load calculations

Author	Formula
Kudryashov (1958)	$h_D = d\dfrac{25.91\left(\dfrac{V^2}{gH}-0.251\right)^2+1.08}{\left(\dfrac{V^2}{gH}+0.07\right)^2}$
Go-Zhen (1960)	$h_D = 0.75\dfrac{\omega}{0.8V_0}H$
Snischenko (1980)	$h_D = 0.25H \ when \ H \le 1$ $h_D = 0.2+0.1H \ when \ H > 1$
Kopaliani (1989) (Kopaliani & Gendelman 1989)	$h_D = 0.39d\left(\dfrac{V}{V_0}\right)^{2.5}Fr^{-3.75}$
Snischenko, Kopaliani (1989) (Kopaliani & Gendelman 1989)	$h_D = 2.1\dfrac{d}{Fr^{4.1}}\left(\dfrac{V-V_0}{V_0}\right)^{1.4}$
Noselidze (1992)	$h_D = H\left(0.07\dfrac{V}{V_0}+0.02\right)$
Kostyuchenko, Kopaliani (2006)	$h_D = 0.13H$
Samokhvalova (2011)	$h_D = 0.11H$

Note: ω – mean of absolute values of pulsation velocity components, m/s.

Table 4. Dune velocity (C_D, *m/s*) formulas that showed the least error in bed load calculations

Author	Formula
Kudryashov (1958)	$C_D = 0.00788\dfrac{V^4}{H^{\frac{5}{4}}g^{\frac{3}{2}}d^{\frac{1}{4}}} \quad when \ Fr^2 \le 1$ $C_D = \sqrt[3]{\dfrac{Igd^2}{H}} - 2.84\dfrac{gd}{V} \quad when \ Fr^2 \ge 1$
Go-Zhen (1960)	$C_D = 0.26\dfrac{d}{H}\left(V-0.8V_0\right)\dfrac{V^2}{\left(0.8V_0\right)^2}$
Snischenko, Kopaliani, Tvalavadze (1977)	$C_D = 0.032\left(V-V_0\right)\dfrac{V}{V_0}\left(\dfrac{d}{h_D}\right)^{0.7}$
Snischenko, Kopaliani (1978)	$C_D = 0.019VFr^{2.9}$
Kopaliani (1989) (Kopaliani & Gendelman 1989)	$C_D = 0.009V\left(\dfrac{V}{V_0}\right)^2\left(\dfrac{h_D}{d}\right)^{-0.8}$

Table 5. Bed load formulas that showed the least error

Author	Formula
Shamov (1952)	$q_b = \alpha \sqrt[3]{\overline{d}_{max}^{\,2}} \left(\frac{V}{V_0}\right)^3 \left(V - V_0\right)\left(\frac{d}{H}\right)^{0.25}$, $kg/(s \cdot m)$ *a*=3, if the largest fraction in the sediment composition is 40-70% of sample weight, *a*=2.5 – 20-40% or 70-80%, *a*=1.5 – 10-20% or 80-90% $V_0 = 3.83\left(\frac{d_{50}}{d_{90}}\right)^{0.2} d^{\frac{1}{3}} H^{\frac{1}{6}}$, m/s
Goncharov (1962)	1. $q_b = \frac{(1+\varphi)}{800} dV_0 \left(\frac{V^3}{V_0^3} - 1\right)\left(\frac{V}{V_0} - 1\right)$, $m^3/(s \cdot m)$ 2. $q_b = 1.2(1+\varphi)\, dV_0 \left(\frac{V}{V_0}\right)^{4.33}$, $kg/(s \cdot m)$ $V_0 = \lg \frac{8.8H}{d_5} \sqrt{\frac{2g\left(\gamma_s - \gamma\right)d}{3.5\gamma}}$, m/s when *d* = 0.15-0.5 mm, *φ* = 2.25, when *d* = 0.5-1.5 mm *φ* =1.23, when *d* >1.5 mm *φ* = 1.0.
Grishanin (1969)	$q_b = 0.015\left(\frac{V}{V_0}\right)^3 d\left(V - V_0\right)$, $m^3/(s \cdot m)$
Butakov (1998)	$q_b = 0.07\left(\frac{v}{\sqrt{g}}\right)^{\frac{1}{3}} \sqrt{d}\, V_0 \left(\frac{V}{V_0}\right)^3$, $m^3/(s \cdot m)$ $V_0 = 1.25\sqrt{gd}\, \lg \frac{8.8H}{d}$, m/s

Note: *α* – a coefficient, $\overline{d}_{max}$ – average diameter of the largest sediment fraction which is at least 10% of the composition of the mobile part of bed sediments, m, *φ* – turbulence parameter, d_5 – diameter of the largest particles which share is 5%, m (accepted equal to d_{95}), *γ* – specific weight of water, N/m^3, γ_s – specific weight of sediment particles, N/m^3, *v* – kinematic viscosity coefficient, m^2/s.

Table 6. Error of bed load calculations according to the most accurate formulas

№	Author		Mean error, %
	h_D formulas	C_D formulas	
1	Go-Zhen		45
2	Kudryashov		44
3	Kopaliani		37
4	Kostyuchenko, Kopaliani	Kopaliani	33
5	Samokhvalova	"	33
6	Snischenko	"	33
7	Snischenko, Kopaliani	"	39
8	Noselidze	"	34
9	Kopaliani	Snischenko, Kopaliani	49
10	Kostyuchenko, Kopaliani	"	49
11	Samokhvalova	"	56
12	Snischenko	"	49

13	Noselidze	"	49
14	Kostyuchenko, Kopaliani	Snischenko, Kopaliani, Tvalavadze	51
15	Samokhvalova	"	47
16	Snischenko	"	51
17	Noselidze	"	52
	q_b formulas		
18	Butakov		56
19	Goncharov (1)		38
20	Goncharov (2)		38
21	Grishanin		50
22	Shamov		40

Based on these data a verification of 80 bed load formulas has been performed. Among the considered approaches to bed load calculation (bed form approach, critical velocity approach, critical water discharge approach and regression approach) the bed form approach showed the highest productivity.

11 formulas that previously showed a positive result for the conditions of large plain rivers when tested on the data obtained by the iterated lengthwise echo-sounding method confirmed their effectiveness. They can be recommended with greater confidence for practice in conditions when the Froude number is less than 0.2, flow depth is 2.6-16.5 m, flow velocity is 0.5-2.1 m/s, slope is 0.000064-0.000195 and average particle size of bed sediments is 0.3-2.9 mm.

The fact that approximately the same formulas give good results both for the volumetric method presented in this paper and for the iterated lengthwise echo-sounding method, which was used for testing bed load formulas earlier, implicitly indicates the reliability of measuring of bed load transport by iterated lengthwise echo-sounding.

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