Eksperimentalna analiza oscilatornih transportnih platformi za prosejavanje vlažnih materijala

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Oscilatorne platforme koriste se u praksi za obavljanje transportnih i pretovarnih radova prilikom izvođenja najrazličitijih tehnoloških procesa. Većina postojećih konstrukcija dizajnirana je za potrebe transporta suvih i rastresitih materijala, jer je tada radni učinak daleko najveći. Iskustva stečena u eksploataciji u realnim radnim uslovima pokazala su da najveći problemi u radu konkretnih mašina i uređaja nastaju usled naglog povećanja vlažnosti, zbog pojave "lepljivosti" transportovane mase (poljoprivreda, građevinarstvo, rudarstvo).

Da bi se područje primene platformi proširilo i na ekstremne radne uslove, autor je u protekle dve decenije sproveo obimna teorijska istraživanja čije je rezultate prezentirao u okviru objavljenih stručnih radova, dok će rezultati eksperimen-talnih istraživanja biti prezentirani u ovom radu.

Ključne reči: višefaktorni plan eksperimenta, vlažna zemljišna masa, matematički model, oscilatorna transportna platforma, prosejavanje, separacija.

0. UVOD

Kod postojećih mašina i uređaja za transportovanje zemljišne mase pomoću oscilatornih platformi, osnovni zahtevi koje treba ispuniti u toku rada jesu: maksimalan transport, maksimalno razbijanje (usitnjavanje) i maksimalna separacija (izdvajanje) pojedinih komponentnih sastojaka iz čvrste mase.

Poznata je činjenica da je vlažnost zemljišne mase w iskazana u % jedan od najuticajnijih faktora od koga zavise njen transport, separacija i prosejavanje kroz rešetku (sito) oscilatorne platforme. Najbolji radni efekti postižu se pri radu sa suvom i mekom zemljom bez prisustva čvrstih grudvi. Takva zemljana masa korišćena je u toku eksperimentalne faze istraživanja, koju je autor rada realizovao na prototipu oscilatorne platforme (sl. 1) na Tehničkom fakultetu u Čačku i na Institutu za krompir u Guči, za vreme izrade svog magistarskog rada [1]. Pod takvim okolnostima platforma je uvek besprekorno obavljala predviđenu radnu funkciju.

Međutim, iskustvo iz eksploatacije stečeno u protekle dve decenije pokazalo je da problemi u radu oscilatorne platforme nastupaju nakon obilnih kiša, tj. onda kada se vlažnost zemlje w jako poveća. Tada je efekat transporta i separacije najslabiji, zbog lepljenja vlažne zemlje za raonik koji je u tom slučaju veoma teško podkopava. U pojedinim ekstremnim slučajevima, dolazilo je i do potpunog onemogućavanja rada platforme.

Od početka šezdesetih godina prošlog veka, veći broj autora u svetu bavio se konkretnom problematikom povećanja radne sposobnosti platformi, mahom namenjenih za sitnozrnaste i suve materijale.

Teorijske osnove rada ovakvih platformi mogu se naći u odgovarajućoj literaturi [2, 3, 4]. Njihovi fizički modeli imali su svoj razvojni - dijalektički put i to počev od najjednostavnijih sa jednom ili dve mase međusobno povezane elastičnim vezama [5, 6], pa do najsloženijih modela kod kojih je izvršena optimizacija najuticajnijih radnih parametara [7, 8, 9, 10]. Međutim, svi navedeni modeli odnose se uglavnom na transportovanje suve, najčešće zemljane mase i isti mogu biti dobra polazna osnova za formiranje modela oscilatornih platformi za transport vlažnih materijala.

Stoga je autor ovog rada došao na ideju da obavi jedno novo istraživanje spomenute problematike, kojim bi se ustanovilo kakav bi bio rad oscilatorne platforme u ekstremno teškim radnim uslovima i to kod maksimalno vlažne i plastične zemlje (tzv. "teške ilovače"). Istraživanjem je trebalo prihvatiti ili odbaciti postavljene hipoteze, imajući u vidu sve relevantne faktore koji utiču na rad oscilatornih platformi.

Rezultati i zaključci dobijeni jednim ovakvim kompleksnim istraživanjem sigurno bi mogli korisno poslužiti za modifikaciju već postojećih, a takođe i za izradu potpuno novih mašina i uređaja koje u svom radu koriste oscilatorne platforme za separaciju i prosejavanje vlažne zemljišne mase.

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LEGENDA:

- 1 - DOBOŠ;
- 2 - NOŽ (CRTALO);
- 3 - VIBRACIONI RAONIK;
- 4 - OSCILATORNA PLATFORMA;
- 5 - OBRтни TOČAK;
- 6 - NOSEĆI RAM (SKELET);
- 7 - VEŠANJE PLATFORME (LISNATA OPRUGA);
- 8 - TELESKOPSKO VRATILO;
- 9 - TRANSMISIONO VRATILO;
- 10 - EKSCENTARSKO VRATILO;
- 11 - POGONSKA POLUGA EKSCENTRA;
- 12 - TRAKTOR;
- z_1 - z_2 - KONUSNI ZUPČASTI PAR.

Sl. 1. Šematski prikaz eksperimentalne oscilatorne platforme ugrađene na vibracionoj vadilici krompira tipa VWK-10

1. OPŠTE POSTAVKE I NAČELA U VEZI PROSEJAVANJA VLAŽNE ZEMLJIŠNE MASE

Iz do sada iznetih teorijskih analiza rada oscilatorne platforme [1÷10] može se zaključiti da koeficijent potpunosti (finoće) separacije η zavisi od četiri uticajna faktora: brzine oscilovanja (ωA), vlažnosti zemlje (w), veličine otvora na rešetki (d) i specifičnog napajanja platforme zemljom (Q_{sp}). U proceduri koja dalje sledi ispitivaće se da li su sve četiri spomenute veličine zaista signifikantne veličine, odnosno da li je opravdano pisati da je:

$$\eta = f(\omega A; w; d; Q_{sp}) \quad (1)$$

Međutim, u toku prve faze istraživanja koje je obavljeno na Tehničkom fakultetu u Čačku na eksperimentalnoj platformi ugrađenoj na vibracionoj vadilici krompira VWK-10 [11], konstantovano je da pri separaciji suve i neugrudvane zemlje koeficijent potpunosti separacije η zavisi od brzine oscilovanja samo negde do $\omega A \approx 1 \text{ m/s}$. Iznad te brzine ($\omega A > 1 \text{ m/s}$) koeficijent potpunosti separacije ima konstantno visoku vrednost ($\eta \approx 0,98$), što znači da skoro sva zemlja pristigla na platformu biva u potpunosti prosejana. Ispod navedene brzine ($\omega A < 1 \text{ m/s}$) ovaj koeficijent je nešto manji i iznosi $\eta \approx 0,92 \div 0,98$, na osnovu čega je izveden zaključak da je rad oscilatornih platformi sa brzinama oscilovanja manjim od 1 m/s neracionalan [1] i da ga treba izbegavati.

Do gotovo identičnog zaključka došli su i istraživači u bivšem SSSR-u [12] kada je u pitanju separacija suve i neugrudvane zemlje.

Oni su istovremeno vršili i oglede sa vlažnom i plastičnom zemljom, gde su takođe dokazali da pri brzinama oscilovanja $\omega A < 1 \text{ m/s}$ koeficijent finoće separacije približno iznosi $\eta \approx 0,5 \div 0,6$, dok pri brzinama oscilovanja $\omega A > 1 \text{ m/s}$ isti se ustaljuje na vrednost od $\eta \approx 0,62$.

Time su dokazali da prethodno izneti zaključak važi i za separaciju vlažne i plastične zemlje, gde je takođe neracionalan rad oscilatornih platformi sa brzinama oscilovanja manjim od 1 m/s i da ga u praksi treba izbegavati. Rezultate svojih istraživanja oni su prikazali preko *dijagrama separacije* koji je dat na sl. 2.

Sl. 2. Zavisnost koeficijenta potpunosti (finoće) separacije od brzine oscilovanja platforme (1-suva i neugrudvana zemlja; 2-vlažna i plastična zemlja; ogledni parametri: $A=20 \text{ mm}$; $d=25 \text{ mm}$; $Q_{sp}=40 \text{ kg/(s} \cdot \text{m)}$)

Zbog navedene preporuke, naša eksperimentalna platforma ugrađena na vadilici krompira VWK-10, ima sledeće radne parametre:

- $f = 10,8 \text{ Hz}$ – frekvencija oscilovanja platforme (broj potkopavanja zemlje raonikom u jednoj sekundi);
- $\omega = 2\pi \cdot f = 2\pi \cdot 10,8 = 68 \text{ s}^{-1}$ – kružna frekvencija oscilovanja platforme;
- $A = 20 \text{ mm} = 0,02 \text{ m}$ – amplituda oscilovanja platforme (poluprečnik ekscentra ekscentarskog vratila);
- $\omega A = 68 \cdot 0,02 = 1,36 \text{ m/s}$ – brzina oscilovanja platforme.

Imajući na umu iznetu činjenicu da dalji porast brzine oscilovanja iznad $1,36\text{ m/s}$ ne bi doveo do nikakvog povećanja koeficijenta finoće separacije (ni kod suve ni kod vlažne zemlje), brzina oscilovanja ωA može se sasvim slobodno izostaviti iz (1), tako da će u našoj verziji eksperimenta η biti funkcija od tri karakteristične veličine:

$$\eta = f(w; d; Q_{sp}) \quad (2)$$

2. PLAN IZVOĐENJA EKSPERIMENTA

Na osnovu (2) može se zaključiti da sva tri navedena faktora w , d , Q_{sp} imaju karakter ulaznih veličina tj. nezavisno promenljivih veličina (x_1 , x_2 , x_3), dok faktor η koji nastaje kao posledica dejstva ulaznih veličina predstavlja funkciju cilja (funkciju odziva), imajući pri tome karakter zavisno promenljive veličine (y).

To praktično znači sledeće: spomenuti faktori w , d , Q_{sp} biće varirani u toku eksperimenta i to u intervalu od njihovih minimalnih do maksimalnih propisanih vrednosti, odnosno biće varirani u intervalima: ($w_{min} \div w_{max}$), ($d_{min} \div d_{max}$), ($Q_{spmin} \div Q_{spmax}$), kako bi se ustanovio uticaj istih na veličinu η .

Sam eksperiment biće izveden prema unapred utvrđenom ortogonalnom planu 2^3 bez uzimanja u obzir međusobne interakcije faktora (w , d , Q_{sp}), a analiza dobijenih rezultata biće izvršena po metodologiji koja je u vidu algoritma data na sl. 3. Ovakva metodologija eksperimenta omogućuju uzimanje u obzir velikog broja faktora o kojima se nema neko veće prethodno iskustvo, a takođe i to da se posle delimičnih eksperimenata iz dalje analize eliminišu oni faktori koji uza sebe nemaju signifikantne (značajne) koeficijente.

Shodno raspoloživim informacijama, biće izvršen izbor *faktorskih nivoa* imajući u vidu postavljeni cilj eksperimenta, a ne zalazeći mnogo u neku dublju suštinu problema koji se istražuje. Gornji i donji nivoi (maksimalne i minimalne vrednosti uticajnih faktora) odabiraju se shodno postojećim podacima i preporukama iz literature, dok se srednji nivoi dobijaju proračunom kao odgovarajuće srednje vrednosti.

• VLAŽNOST ZEMLJE •

Pošto se ispituje rad platforme u ekstremno teškim i nepovoljnim radnim uslovima, u [12] istaknuto je da se kao *zona loše separacije* tretira područje rada platforme sa doturenom zemljom čija se vlažnost nalazi u opsegu $w=(23 \div 27)\%$. Iz tog razloga usvajaju se sledeće karakteristične vrednosti:

$$w_{max} = 27\%;$$

$$w_{min} = 23\%;$$

$$w_{sr} = \sqrt{w_{max} \cdot w_{min}} = \sqrt{27 \cdot 23} = 24,92\%$$

Usvaja se: $w_{sr} = 25\%$.

• VELIČINA OTVORA NA REŠETKI •

Kao optimalna vrednost veličine otvora (perforacija na rešetki) platforme pri radu sa suvom i neugrudvanom zemljom [1] usvojeno je $d=25\text{ mm}$, što se ujedno uzima i kao najmanja dozvoljena vrednost pri radu sa vlažnom zemljom. Kao najveća preporučena vrednost (imajući na umu namenu platforme-u ovom slučaju mašina za vađenje krompira) usvaja se $d=45\text{ mm}$.

$$d_{max} = 45\text{ mm};$$

$$d_{min} = 25\text{ mm};$$

$$d_{sr} = \sqrt{d_{max} \cdot d_{min}} = \sqrt{45 \cdot 25} = 33,54\text{ mm}$$

Usvaja se: $d_{sr} = 35\text{ mm}$.

• SPECIFIČNO NAPAJANJE ZEMLJOM •

Preporučene vrednosti ovog faktora iznose [11]:

$$Q_{spmax} = 70\text{ kg/(s} \cdot \text{m)};$$

$$Q_{spmin} = 20\text{ kg/(s} \cdot \text{m)};$$

$$Q_{spsr} = \sqrt{Q_{spmax} \cdot Q_{spmin}} = \sqrt{70 \cdot 20} = 37,42\text{ kg/(s} \cdot \text{m)}$$

Usvaja se: $Q_{spsr} = 40\text{ kg/(s} \cdot \text{m)}$.

Sl. 3. Metodologija realizacije eksperimenata

Odabrani faktorski nivoi mogu se skupa prikazati pomoću tabele T.1.

Tabela T.1. Faktorski nivoi uticajnih faktora u eksperimentu

ФАКТОРИ	VLAŽNOST ZEMLJE w [%]	VELIČINA OTVORA NA REŠETKI d [mm]	SPECIFIČNO NAPAJANJE ZEMLJOM Q_{sp} [kg/(s·m)]
NIVOI			

MAKSIMALNI	27	45	70
SREDNJI	25	35	40
MINIMALNI	23	25	20

Kao plan eksperimenta usvaja se *trofaktorni ortogonalni plan* 2^3 sa po jednim merenjem u svakoj tački plana i sa ponavljanjem merenja u nultoj tački plana četiri puta (radi veće tačnosti izmerenih rezultata), pri čemu se neće uzimati u obzir međusobna interakcija faktora: w , d , Q_{sp} .

Spomenuti plan bez uzimanja u obzir međusobnih uticaja faktora i sa isplaniranim redosledom izvođenja eksperimenata prikazan je u tabeli T.2.

Tabela T.2. Plan-matrica za izvođenje eksperimenata*

EKSP. TAČKA	VLAŽNOST ZEMLJE w [%]	VELIČINA OTVORANA REŠETKI d [mm]	SPECIFIČNO NAPAJANJE ZEMLJOM Q_{sp} [kg/(s·m)]	PLAN-MATRICA			
				x_0	x_1	x_2	x_3
1	27	45	70	1	1	1	1
2	23	45	70	1	-1	1	1
3	27	25	70	1	1	-1	1
4	23	25	70	1	-1	-1	1
5	27	45	20	1	1	1	-1
6	23	45	20	1	-1	1	-1
7	27	25	20	1	1	-1	-1
8	23	25	20	1	-1	-1	-1
9	25	35	40	1	0	0	0
10	25	35	40	1	0	0	0
11	25	35	40	1	0	0	0
12	25	35	40	1	0	0	0

*Napomena: Radi uprošćenja pri upisivanju i obradi eksperimentalnih podataka u plan-matrici, razmere za koordinatne ose biraju se tako da maksimalni (gornji nivo) bude jednak +1, minimalni (donji nivo) bude jednak -1, a srednji (nulti) nivo bude ravan nuli (0).

Na slici 4 šematski je prikazan trofaktorni ortogonalni plan izvođenja eksperimenata sa četiri ponavljanja merenja u nultoj tački plana.

Sl. 4. Trofaktorni ortogonalni plan izvođenja eksperimenata

Osnovni podaci o eksperimentu:

$k=3$ - broj uticajnih faktora u eksperimentu

($x_1 \equiv w$; $x_2 \equiv d$; $x_3 \equiv Q_{sp}$);

$n_0=4$ - broj ponavljanja merenja u nultoj tački plana;

$N_e = 2^k + n_0 = 2^3 + 4 = 12$ - ukupan broj merenja (eksperimenata).

3. USLOVI I REŽIMI ISPITIVANJA I REZULTATI MERENJA

Celokupno merenje obavljeno je na jednositoj eksperimentalnoj platformi ugrađenoj na vibracionoj vadilici krompira tipa VWK-10 (sl. 1).

Cilj planiranog eksperimenta nije ispitivanje potkopavajućih i transportnih sposobnosti platforme, nego ispitivanje sposobnosti u pogledu njene separacije i prosejavanja. Iz tog razloga, radi lakšeg merenja uticajnih parametara, zemlja nije potkopavana uz pomoć raonika, već je na platformu stovarana direktno sa traktorske prikolice pomoću korita (levka).

Na prikolici je zemlja pomoću creva polivana vodom u cilju postizanja potrebne vlažnosti w , koja je merena na licu mesta uz pomoć aparature kojom raspolaže Agronomski fakultet u Čačku.

Pre toga, zemlja je istovarana na prikolicu iz plastičnih buradi, čija je masa prethodno izmerena na vagi. Brzina istovara zemlje iz prikolice, tj. brzina napajanja platforme zemljom kontrolisana je uz pomoć štoperice, nastojeći pri tome da se ista izručuje što ravnomernije po celoj površini rešetke i time što preciznije obezbedi potrebno specifično napajanje Q_{sp} [kg/(s·m)].

Treći uticajni parametar-veličina otvora na rešetki (d) variran je tako što su čelične trake od kojih se sastoji rešetka međusobno udaljavane jedna od druge na potrebno rastojanje i potom fiksirane u tom novom položaju pomoću navojnih osovinica. Ovo je moguće zahvaljujući tome što u nosećem ramu-skeletu platforme (pozicija 6 na sl. 1) postoje unapred izbušeni otvori u koje se postavljaju navojne osovinice.

Da bi se tačno ustanovila masa prosejane zemlje u toku eksperimenta, ispod rešetke platforme (koja stoji u mestu) pre početka merenja postavlja se tabla lima na koju pada prosejana zemlja u toku rada platforme. Nakon zaustavljanja platforme prosejana zemlja lopatama se skida sa limene table i tovari u plastičnu burad čija se masa ponovo meri pomoću vage. Deljenjem izmerene mase prosejane zemlje (na kraju eksperimenta) sa izmerenom masom doturene zemlje (na početku eksperimenta) dobija se vrednost koeficijenta potpunosti separacije η za određenu eksperimentalnu tačku. Postupak je potrebno ponoviti dvanaest puta, za svaku eksperimentalnu tačku ponosaob.

Shodno usvojenom planu eksperimenta (tabela T.2) svi relevantni faktori: w , d , Q_{sp} kontrolisani su i varirani u granicama od +1 do -1, a izmerene vrednosti koeficijenta potpunosti separacije η za svih dvanaest izvršenih merenja unete su u tabelu T.3.

Tabela T.3. Izmerene vrednosti koeficijenta η u toku eksperimenata

EKSP. TAČKE	1	2	3	4	5	6	7	8	9	10	11	12
KOEFIC. η	14	58	6	48	16	60	10	50	25	24	26	22
$y_i = \ln(\eta)$	2.64	4.06	1.79	3.87	2.77	4.09	2.30	3.91	3.22	3.18	3.26	3.09

4. REGRESIONA ANALIZA

Ova analiza obuhvata određivanje regresionih koeficijenata b_i , čime se dobija predstava o uticaju pojedinih faktora na izlaznu funkciju η . Ukoliko se ovom analizom dobiju faktori uz koje stoje nesignifikantni koeficijenti, isti se neće uzimati u obzir pri daljim razmatranjima. Znak regresionog koeficijenta b_i pruža uvid o tipu uticaja datog faktora na izučavani proces, pri čemu znak plus (+) ozna-

čava direktno proporcionalan, a znak minus (-) označava obrnuto proporcionalan uticaj na merenu veličinu η .

Opšti matematički model bez međusobnog uticaja faktora x_1, x_2, x_3 prema [13] ima sledeći oblik:

$$y = b_0 \cdot x_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 \quad (3)$$

U jednačini (3) pojedine oznake imaju sledeće značenje:

y – logaritamska vrednost merene veličine;

b_0, b_1, b_2, b_3 – koeficijenti regresije koji se sračunavaju regresionom analizom.

Radi veće pouzdanosti proračuna, ukupan broj merenja trofaktornog ($k=3$) ortogonalnog plana uvećava se za $n_0=4$ ponavljanja merenja u nultoj tački plana:

$$N_e = 2^k + n_0 = 2^3 + 4 = 12 \quad (4)$$

Dalja analiza teče pomoću matričnog računa [13], na osnovu koga neposredno slede regresioni koeficijenti (b_i):

$$b_0 = (1/12) \cdot (38,18) = 3,182$$

$$b_1 = (1/8) \cdot (-6,43) = -0,804$$

$$b_2 = (1/8) \cdot (1,69) = 0,211$$

$$b_3 = (1/8) \cdot (-0,71) = -0,089 \quad (5)$$

Pošto su sada koeficijenti regresije b_i poznati, može se napisati matematički model u kodiranom obliku:

$$y = b_0 \cdot x_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 \quad (x_0=1)$$

$$y = 3,182 - 0,804 \cdot x_1 + 0,211 \cdot x_2 - 0,089 \cdot x_3 \quad (6)$$

5. DISPERZIONA ANALIZA

Pomoću disperzione analize određuje se signifikantnost regresionih koeficijenata b_i , a takođe i adekvatnost matematičkog modela. Kompletna disperziona analiza izvodi se postupno prema metodologiji navedenoj u [13].

I) Broj stepeni slobode:

$$f_r = N_e - k - 1 = 12 - 3 - 1 = 8$$

$$f_e = n_0 - 1 = 4 - 1 = 3$$

$$f_a = f_r - f_e = 8 - 3 = 5$$

$$(f_0 = 1; f_1 = 1; f_2 = 1; f_3 = 1)$$

II) Sume kvadrata:

$$s_{b0} = N_e \cdot b_0^2 = 12 \cdot 3,182^2 = 121,5015$$

$$s_{b1} = N \cdot b_1^2 = 8 \cdot (-0,804)^2 = 5,1713$$

$$s_{b2} = N \cdot b_2^2 = 8 \cdot 0,211^2 = 0,3562$$

$$s_{b3} = N \cdot b_3^2 = 8 \cdot (-0,089)^2 = 0,0634$$

III) Rezidualna suma:

$$s_r = \sum_{i=1}^{12} y_i^2 - \left(N_e \cdot b_0^2 + \sum_{i=1}^3 N \cdot b_i^2 \right)$$

$$s_r = \left(2,64^2 + 4,06^2 + 1,79^2 + 3,87^2 + 2,77^2 + 4,09^2 + 2,30^2 + 3,91^2 + 3,22^2 + 3,18^2 + 3,26^2 + 3,09^2 \right) - (121,5015 + 5,1713 + 0,3562 + 0,0634) = 0,1774$$

IV) Greška eksperimenta u nultoj tački plana:

$$\overline{y_0} = \frac{3,22 + 3,18 + 3,26 + 3,09}{4} = 3,1875$$

$$s_e = \sum_{i=1}^{12} (y_{oi} - \overline{y_0})^2 = (3,22 - 3,1875)^2 + (3,18 - 3,1875)^2 + (3,26 - 3,1875)^2 + (3,09 - 3,1875)^2 = 0,0159$$

V) Adekvatna suma:

$$s_a = s_r - s_e = 0,1774 - 0,0159 = 0,1615$$

VI) Disperzije:

$$s_{b0}^2 = \frac{s_{b0}}{f_0} = \frac{121,5015}{1} = 121,5015$$

$$s_{b1}^2 = \frac{s_{b1}}{f_1} = \frac{5,1713}{1} = 5,1713$$

$$s_{b2}^2 = \frac{s_{b2}}{f_2} = \frac{0,3562}{1} = 0,3562$$

$$s_{b3}^2 = \frac{s_{b3}}{f_3} = \frac{0,0634}{1} = 0,0634$$

$$s_r^2 = \frac{s_r}{f_r} = \frac{0,1774}{8} = 0,0222$$

$$s_e^2 = \frac{s_e}{f_e} = \frac{0,0159}{3} = 0,0053$$

$$s_a^2 = \frac{s_a}{f_a} = \frac{0,1615}{5} = 0,0323$$

VII) Računsko određivanje Fišerovih "F-vrednosti":

$$F_{r0} = \frac{s_{b0}^2}{s_e^2} = \frac{121,5015}{0,0053} = 22924,8 ;$$

$$F_{r1} = \frac{s_{b1}^2}{s_e^2} = \frac{5,1713}{0,0053} = 975,7 ;$$

$$F_{r2} = \frac{s_{b2}^2}{s_e^2} = \frac{0,3562}{0,0053} = 67,2 ;$$

$$F_{r3} = \frac{s_{b3}^2}{s_e^2} = \frac{0,0634}{0,0053} = 11,96 ;$$

$$F_{ra} = \frac{s_a^2}{s_e^2} = \frac{0,0323}{0,0053} = 6,1 ;$$

VIII) Signifikantnost regresionih koeficijenata:

Za određivanje značajnosti regresionih koeficijenata biće primenjen Fišerov "F-test", pri čemu se usvaja da koeficijent rizika iznosi 5% ($\alpha=0,05$).

$$F_t(\alpha; f_i; f_e) = F_t(0,05; 1; 3) = 10,13 \text{ (prema [13])}.$$

Dalje se ispituje da li je svaka računaska vrednost Fišerove "F-karakteristike" veća od tablične vrednosti, odnosno proverava se da li je u svakom konkretnom slučaju ispunjen potreban uslov:

$$F_{ri} > F_t \quad (7)$$

$$F_{ro} > F_t; \quad F_{r1} > F_t; \quad F_{r2} > F_t; \quad F_{r3} > F_t \quad (8)$$

Iz (8) može se uočiti da je potreban uslov (7) zadovoljen u slučaju svih koeficijenata, što znači da se sa rizikom od 5% sme tvrditi da su svi regresioni koeficijenti: b_o, b_1, b_2, b_3 *signifikantni-značajni*, tj. da su sasvim opravdano uvršćeni u regresionu jednačinu (6) koja predstavlja kodirani oblik matematičkog modela.

IX) Adekvatnost matematičkog modela:

Ovde se takođe može primeniti Fišerov "F-test", usvajajući i u ovom slučaju da koeficijent rizika iznosi 5% ($\alpha=0,05$).

$$F_t(\alpha; f_a; f_e) = F_t(0,05; 5; 3) = 9,01 \quad (\text{prema [13]}).$$

U ovom slučaju potrebno je da bude ispunjen sledeći uslov:

$$F_{ra} < F_t \quad (9)$$

$$(F_{ra}=6,1) < (F_t=9,01) \quad (10)$$

Iz jednačine (10) može se uočiti da je potreban uslov (9) ispunjen, što znači da dobijeni matematički model u potpunosti opisuje proučavanu problematiku u vezi separacije i prosejavanja vlažne zemljišne mase na oscilatornoj platformi. Isti je prema tome *adekvatan*, uz napomenu da koeficijent rizika za ovakvu tvrdnju iznosi prethodno usvojenih 5% ($\alpha=0,05$).

6. DEKODIRANJE MATEMATIČKOG MODELA

Matematički model u dekodiranom obliku ima sledeći oblik [13]:

$$y = B_o \cdot x_1^{\beta_1} \cdot x_2^{\beta_2} \cdot x_3^{\beta_3} \quad (11)$$

Nivoi ulaznih veličina:

$$x_{1\max}=27; \quad x_{2\max}=45; \quad x_{3\max}=70;$$

$$x_{1\min}=23; \quad x_{2\min}=25; \quad x_{3\min}=20;$$

Koeficijent B_o računa se po obrascu:

$$B_o = e^{\beta_0} \quad (12)$$

EkspONENT u jednačini (12) računa se po obrascu:

$$\beta_o = b_o + b_1 \cdot a_1 + b_2 \cdot a_2 + b_3 \cdot a_3 \quad (13)$$

U jednačini (13) koeficijenti a_i ($i=1, 2, 3$) računaju se na sledeći način:

$$a_1 = 1 - A_1 \cdot \ln(x_{1\max}) = 1 - 12,47 \cdot \ln 27 = -40,099$$

$$a_2 = 1 - A_2 \cdot \ln(x_{2\max}) = 1 - 3,40 \cdot \ln 45 = -11,943$$

$$a_3 = 1 - A_3 \cdot \ln(x_{3\max}) = 1 - 1,60 \cdot \ln 70 = -5,798$$

Koeficijenti A_i ($i=1, 2, 3$) imaju sledeće vrednosti:

$$A_1 = \frac{2}{\ln \frac{x_{1\max}}{x_{1\min}}} = \frac{2}{\ln \frac{27}{23}} = 12,47$$

$$A_2 = \frac{2}{\ln \frac{x_{2\max}}{x_{2\min}}} = \frac{2}{\ln \frac{45}{25}} = 3,40$$

$$A_3 = \frac{2}{\ln \frac{x_{3\max}}{x_{3\min}}} = \frac{2}{\ln \frac{70}{20}} = 1,60$$

Smenom nađenih koeficijenata a_1, a_2, a_3 i prethodno sračunatih regresionih koeficijenata b_o, b_1, b_2, b_3 u jednačinu (13), dobija se:

$$\beta_o = 3,182 + (-0,804) \cdot (-40,099) + 0,211 \cdot (-11,943) + (-0,089) \cdot (-5,798) = 33,418$$

Smenom sračunatog eksponenta β_o u (12) dobija se:

$$B_o = e^{33,418} = 3,26 \cdot 10^{14}$$

Sada je moguće sračunati vrednosti i svih ostalih eksponentata:

$$\beta_1 = A_1 \cdot b_1 = 12,47 \cdot (-0,804) = -10,03$$

$$\beta_2 = A_2 \cdot b_2 = 3,40 \cdot 0,211 = 0,72$$

$$\beta_3 = A_3 \cdot b_3 = 1,60 \cdot (-0,089) = -0,14$$

Smenom svih nađenih vrednosti u jednačinu (11) dobija se konačna vrednost matematičkog modela u dekodiranom obliku:

$$y = 3,26 \cdot 10^{14} \cdot x_1^{-10,03} \cdot x_2^{0,72} \cdot x_3^{-0,14}$$

$$y = 3,26 \cdot 10^{14} \frac{x_2^{0,72}}{x_1^{10,03} \cdot x_3^{0,14}} \quad (14)$$

Imajući u vidu da je: $y \equiv \eta$, $x_1 \equiv w$, $x_2 \equiv d$, $x_3 \equiv Q_{sp}$, jednačina (14) može se napisati u konačnom obliku koji predstavlja eksperimentalno dobijen matematički model procesa separacije i prosejavanja vlažne zemljišne mase na oscilatornoj platformi:

$$\eta = 3,26 \cdot 10^{14} \frac{d^{0,72}}{w^{10,03} \cdot Q_{sp}^{0,14}} \quad (15)$$

7. ANALIZA EKSPERIMENTALNIH REZULTATA

Iz eksperimentalno dobijenog matematičkog modela (15) zapaža se da sa porastom veličine otvora na rešetki ($d \uparrow$) koeficijent finoće separacije raste ($\eta \uparrow$), što znači da se u tom slučaju radi o *direktnoj proporcionalnosti*.

Nasuprot tome, sa porastom vlažnosti zemlje ($w \uparrow$) i porastom vrednosti specifičnog napajanja platforme zemljom ($Q_{sp} \uparrow$) koeficijent finoće separacije opada ($\eta \downarrow$), što

znači da je u pitanju *obrnuta proporcionalnost* između navedenih faktora.

Tako je, shodno tabelama T.2 i T.3 maksimalna vrednost koeficijenta finoće separacije dobijena u eksperimentalnoj tački 6 ($\eta=60\%$, za $w_{min}=23\%$, $d_{max}=45mm$, $Q_{spmin}=20kg/(s\cdot m)$), dok je minimalna vrednost koeficijenta finoće separacije dobijena u eksperimentalnoj tački 3 ($\eta=6\%$, za $w_{max}=27\%$, $d_{min}=25mm$, $Q_{spmax}=70kg/(s\cdot m)$).

Upoređivanjem vrednosti eksponenata u (15) može se zaključiti da najveći uticaj na koeficijent finoće separacije η ispoljava vlažnost zemlje ($|\beta_1|=10,03$), znatno manji uticaj ima veličina otvora na rešetki ($|\beta_2|=0,72$), a najmanji uticaj ispoljava specifično napajanje platforme zemljom ($|\beta_3|=0,14$). Zato se spomenuti uticaji mogu prikazati sledećom nejednačinom:

$$|\beta_1| > |\beta_2| > |\beta_3| \quad (16)$$

Ako se ponovo proanalizira nejednačina (16), zapaža se da je specifično napajanje platforme zemljom Q_{sp} najmanje uticajan faktor na separaciju i prosejavanje vlažne zemljišne mase (jer je eksponent $|\beta_3|=0,14$). Sledeći faktor po rangu značajnosti jeste veličina otvora na rešetki d (eksponent $|\beta_2|=0,72$), a daleko najuticajniji faktor jeste vlažnost zemlje w (eksponent $|\beta_1|=10,03$).

Iz navedenog razloga, a u cilju lakšeg i jednostavnijeg grafičkog prikazivanja, moguće je izvršiti uprošćenje i smatrati da je $Q_{sp} \approx \text{const}$, dok se ostala dva uticajna faktora – vlažnost zemlje i veličina otvora na rešetki tretiraju kao varijabilne veličine ($w \neq \text{const}$, $d \neq \text{const}$).

Grafički prikaz optimizacije uticajnih parametara na separaciju i prosejavanje vlažne zemljišne mase dat je na slici 5.

Sl. 5. Optimizacija radnih parametara uticajnih na separaciju i prosejavanje vlažne zemljišne mase pomoću oscilatorne transportne platforme

8. ZAKLJUČAK

Prosejavanje vlažnih materijala pomoću mašina i uređaja sa ugrađenim oscilatornim platformama predstavlja

veoma složen i kompleksan proces, za čiju je uspešnu realizaciju neophodan multidisciplinarni pristup [14].

S obzirom na brojna međusobno suprotstavljena ograničenja i na relativno veliki broj uticajnih faktora, spomenuti zadatak treba tretirati kao svojevrsan optimizacioni proces. Ispunjavanje jednog kriterijuma optimizacije često može dovesti do neispunjavanja nekog drugog kriterijuma, pa konačno rešenje, kao i uvek u sličnim situacijama, mora predstavljati kompromis.

Stoga se mogu iskazati sledeći konkretni zaključci u vezi finoće separacije vlažne zemljišne mase:

- **Zaklj. 1:** Vlažnost zemlje w je daleko najuticajniji faktor na finoću separacije η ($|\beta_1|=10,03$ prema (15)), pa ako je $w > 27\%$ rad oscilatorne platforme postaje potpuno neefikasan i nepreporučljiv zbog drastičnog pada njene proizvodnosti. Nikakve dodatne konstrukcione mere ne mogu mnogo doprineti efikasnijem radu platforme u ovako otežanim radnim uslovima.

- **Zaklj. 2:** Veličina otvora na rešetki d je približno 14 puta manje uticajan faktor od vlažnosti zemlje w na finoću separacije η ($|\beta_2|=0,72$ prema (15)) i njegovo povećanje ima efekta samo do vlažnosti $w \approx 25\%$. Iznad ove vlažnosti η se ne povećava čak ni pri osetnijem povećanju veličine otvora na rešetki.

- **Zaklj. 3:** Specifično napajanje Q_{sp} tj. dotur zemlje na platformu je najmanje uticajan faktor na finoću separacije η ($|\beta_3|=0,14$ prema (15)) i njegovo povećanje iznad gornje granice može prouzrokovati samoistovarivanje zemljišne mase i znatno smanjenje veličine η . U praksi je potrebno za svaku platformsku mašinu ponaosob najpre eksperimentalno ustanoviti, a potom i propisati optimalnu tovarnu vrednost faktora Q_{sp}

- **Zaklj. 4:** Zbog činjenice da su sva tri pretpostavljena uticajna faktora (w , d , Q_{sp}) zaista *signifikantni faktori*, kao i zbog eksperimentalno dokazane *adekvatnosti matematičkog modela*, pretpostavka data jednačinom (2) može se u potpunosti prihvatiti, uz koeficijent rizika od 5% prema Fišerovom "F"-kriterijumu koji je jedan od najprihvaćenijih kriterijuma u matematičkoj statistici.

Iz svega izloženog može se zaključiti da je optimizacija uticajnih parametara veoma bitna za postizanje maksimalne proizvodnosti oscilatornih platformi za prosejavanje i separaciju vlažne zemljišne mase [15]. Kako se u današnje vreme od transportnih mašina i uređaja zahtevaju sve veća sigurnost, pouzdanost i stabilnost u radu i pri najtežim radnim uslovima, to je potrebno još u fazi konstruisanja ispuniti sve navedene zahteve. To je jedina garancija da će platformske mašine u realnim eksploatacionim uslovima funkcionisati na obostrano zadovoljstvo, kako proizvođača, tako i korisnika konkretnih mašina i uređaja.

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The Experimental Analysis of the Oscillatory Transporting Platforms for Sieving Moist Materials

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Oscillatory platforms are used in practice for the performance of transportation and transshipment operations while performing various technological processes. Most of the existing constructions are designed for transport of dry and loose materials, because operating effect is the largest in these cases. The experiences gained in exploitation under real operating conditions have shown that the biggest problems in the operation of specific machines and equipment arise from the sudden increase of moisture, due to emergence of the "stickiness" of transported mass (agriculture, building engineering, mining).

In order to extend the scope of application of platforms to extreme operating conditions, the author of the paper conducted extensive theoretical researches in the past two decades and presented the results in the context of published papers, while the results of experimental research will be presented in this paper.

Keywords: multifactor plan of experiment, wet land mass, mathematical model, oscillatory transporting platform, sieving, separation.

0. INTRODUCTION

Nowadays, with existing machines and devices for transportation of land mass by means of oscillatory platform, the basic requirements that must be met are: maximal transportation, maximal breaking (fragmentation) and maximal separation (segregation) of some component ingredients from solid mass.

It is known that the humidity of the land mass w expressed in percentage is one of the most influential factors on which transportation, separation and sieving through a grid (sieve) of oscillatory platform depend. The best operating effects are achieved when working with dry and soft land with no solid lumps. Such land mass is used during the experimental phase of the research carried out by the author on the prototype of oscillatory platform (Fig. 1) at the Technical Faculty in Čačak and at the Institute for Potato in Guča, during the drafting of his MA thesis [1]. Under such circumstances, the platform has always perfectly performed its operating function.

However, experience acquired through the exploitation during last two decades has shown that problems in the work of the oscillating platform occur after heavy rains, i.e. when the land mass moisture w is highly increased. Then the effect of transportation and separation is the weakest, due to sticking of wet land mass to plough, in which case it is extremely difficult to dig the land. In some extreme cases, the platform failed to function.

Since the early 1960s, a great number of authors worldwide dealt with the specific problems of increasing the work efficiency of platforms mainly intended for fine-grained and dry materials.

Theoretical basis of the work of these platforms can be found in the relevant literature [2, 3, 4]. Their physical models had their developmental and dialectical way starting from the simplest models with one or two masses interconnected by elastic links [5, 6], to the most complex models in which optimization of the most influential operating parameters was performed [7, 8, 9, 10]. However, all the models mentioned above refer mainly to the transportation of dry, usually earthen mass and they can be a good starting point for the creation of models of oscillatory platforms for transportation of wet materials.

Therefore, the authors of this paper had the idea to do a new study of this problem in order to determine the operation of oscillatory platform in extremely hard working conditions with maximally moist and plastic land (so called "heavy loam"). The research involved either acceptance or rejection of the proposed hypothesis, having in mind the all relevant factors affecting the operation of oscillatory platforms.

The results and conclusions obtained by such a complex research can certainly be applied for the modification of existing machines and devices, and also for the development of completely new machinery and equipment which use oscillatory platforms for separation and sieving of wet land mass.

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LEGEND:

- 1 – BRAKE DRUM;
- 2 – CIRCULAR KNIFE;
- 3 – PLOUGH;
- 4 – OSCILLATORY PLATFORM;
- 5 – ROTATING WHEEL;
- 6 – FRAME (SUPPORTER);
- 7 – PLATFORM SUSPENSION (LEAF SPRING);
- 8 – TELESCOPIC SHAFT;
- 9 – TRANSMISSION SHAFT;
- 10 – ECCENTRIC SHAFT;
- 11 – DRIVING LEVER OF ECCENTRIC SHAFT;
- 12 – TRACTOR;
- z₁-z₂ – CONICAL GEAR WHEELS.

Fig. 1. Schematic view of the experimental vibrating oscillatory platform mounted on vibratory potato harvester type VWK-10

1. GENERAL ITEMS AND PRINCIPLES FOR SIEVING WET LAND MASS

Theoretical analysis of the operation of oscillatory platform [1÷10] leads to the conclusion that the coefficient of completeness (finesness) of separation η depends on four influential factors: oscillation velocity (ωA), moisture of land mass (w), size of the grid hole (d) and specific supply of the platform with land mass (Q_{sp}). The following procedure will test whether all these four parameters are significant factors indeed, i.e. whether it is justified to write that:

$$\eta = f(\omega A; w; d; Q_{sp}) \quad (1)$$

However, during the first phase of the research which was done at the Technical Faculty in Cacak on the experimental platform built in the vibrational potato digger VWK-10 [11], it was found that during the separation of dry and friable land mass the coefficient of completeness of separation η depends on oscillation velocity up to about $\omega A \approx 1 \text{ m/s}$. Above that velocity ($\omega A > 1 \text{ m/s}$) the coefficient of completeness of separation has a constant high value ($\eta \approx 0.98$), which means that almost all land mass arrived in the platform becomes fully sieved. Below specified velocity ($\omega A < 1 \text{ m/s}$) this coefficient is slightly smaller and its value is $\eta \approx 0.92 \div 0.98$, which contributed to the conclusion that the operation of oscillating platforms whose oscillation velocity values are less than 1 m/s is irrational [1] and that it is necessary to avoid it.

Almost identical conclusion was reached by the researchers in the former Soviet Union [12] when it comes to the separation of dry and friable land mass.

They simultaneously performed experiments with moist and plastic land mass, where they also proved that during oscillation velocity values $\omega A < 1 \text{ m/s}$ the coefficient of completeness of separation is approximately $\eta \approx 0.5 \div 0.6$, while during oscillation velocity values $\omega A > 1 \text{ m/s}$ it has the constant value $\eta \approx 0.62$.

In this way they have proved that previously mentioned conclusion applies both to the separation of wet and plastic land mass, and also that irrational operation of oscillatory platform is the one with oscillation velocity values lower than 1 m/s , which should be avoided in practice. The results of their research were demonstrated through the separation diagram which is given in Fig. 2.

Fig. 2. Dependence of the coefficient of completeness (finesness) of separation on the velocity of platform oscillation (1-dry and friable land; 2-wet and sticky land; experimental parameters: $A=20 \text{ mm}$; $d=25 \text{ mm}$; $Q_{sp}=40 \text{ kg/(s m)}$)

Due to the above recommendations, our experimental platform installed on the potato digger VWK-10 has the following operating parameters:

- $f = 10.8 \text{ Hz}$ – frequency of oscillation of platform (the number of digging land using the plowshare in one second);
- $\omega = 2\pi \cdot f = 2\pi \cdot 10.8 = 68 \text{ s}^{-1}$ – circular frequency of platform oscillation;
- $A = 20 \text{ mm} = 0.02 \text{ m}$ – amplitude of oscillation of platform (the radius of the eccentric shaft);
- $\omega A = 68 \cdot 0.02 = 1.36 \text{ m/s}$ – velocity of platform oscillation.

Considering the fact that a further increase of oscillation velocity values above 1.36m/s would not lead to any increase of the coefficient of completeness of separation (in both cases of dry land mass and wet land mass), oscillation velocity ωA can be freely omitted from (1), so that in our version of the experiment η will be a function of three characteristic parameters:

$$\eta = f(w; d; Q_{sp}) \quad (2)$$

2. PLAN FOR CONDUCTING THE EXPERIMENT

On the basis of (2) it can be concluded that all three abovementioned factors w , d , Q_{sp} have the character of inputs, i.e. independent variables (x_1, x_2, x_3), while the factor η , which occurs as a consequence of inputs, represents the objective function (function of response) having the character of the dependent variable (y).

This means the following: abovementioned factors w , d , Q_{sp} will vary during the experiment in the interval of their minimum to maximum prescribed values, i.e. they will vary in intervals: ($w_{\min} \div w_{\max}$), ($d_{\min} \div d_{\max}$), ($Q_{sp\min} \div Q_{sp\max}$) in order to determine their impact on coefficient η .

The experiment will be performed according to the predetermined orthogonal plan 2^3 without taking into account the interactions of factors (w , d , Q_{sp}), while the analysis of obtained results will be made by the methodology which is in the form of the algorithm given in Fig. 3. This methodology allows taking into account many factors for which there is no previous experience. Besides, it allows, after partial experiments, elimination of those factors which do not contain significant coefficients.

According to available information, the choice of factor levels is performed having in mind the intended aim of the experiment, without going into deeper essence of a research problem. The upper and lower levels (maximal and minimal values of influencing factors) are selected in accordance with existing data and recommendations from the literature, while the middle levels are obtained by means of calculation as the corresponding mean values.

• MOISTURE OF LAND MASS •

The aim of research is to examine the operation of platform under extremely difficult conditions, so in [12] it is outlined that the zone of bad separation is the operation of platform with the land mass whose moisture is in the range $w=(23 \div 27)\%$. For this reason, the following characteristic values are adopted:

$$w_{\max} = 27\%;$$

$$w_{\min} = 23\%;$$

$$w_{sr} = \sqrt{w_{\max} \cdot w_{\min}} = \sqrt{27 \cdot 23} = 24.92\%$$

$$w_{sr} = 25\% \text{ is adopted.}$$

• HOLE SIZE ON THE GRID •

The optimal value of hole size on the grid (perforation on grid) of platform when it operates with dry and friable land mass [1] is adopted as $d=25\text{mm}$, which is also taken as the minimum acceptable value during operation with moist land mass. The highest recommended value (keeping in mind the purpose of platform – in this case machines for extracting the potato) is adopted as $d=45\text{mm}$.

$$d_{\max} = 45\text{mm};$$

$$d_{\min} = 25\text{mm};$$

$$d_{sr} = \sqrt{d_{\max} \cdot d_{\min}} = \sqrt{45 \cdot 25} = 33.54\text{mm}$$

$$d_{sr} = 35\text{mm} \text{ is adopted.}$$

• SPECIFIC SUPPLY WITH LAND MASS •

The recommended values of this factor are [11]:

$$Q_{sp\max} = 70\text{kg}/(\text{s} \cdot \text{m});$$

$$Q_{sp\min} = 20\text{kg}/(\text{s} \cdot \text{m});$$

$$Q_{sp\text{sr}} = \sqrt{Q_{sp\max} \cdot Q_{sp\min}} = \sqrt{70 \cdot 20} = 37.42\text{kg}/(\text{s} \cdot \text{m})$$

$$Q_{sp\text{sr}} = 40\text{kg}/(\text{s} \cdot \text{m}) \text{ is adopted.}$$

Fig. 3. The methodology of experiment performance

Selected factor levels are presented in Table 1.

Table 1. Factor levels of influential factors in the experiment

FACTORS	LAND MASS MOISTURE	HOLE SIZE ON THE GRID	SPECIFIC SUPPLY WITH LAND MASS
LEVELS	w [%]	d [mm]	Q_{sp} [kg/(s·m)]
MAXIMAL	27	45	70
MIDDLE	25	35	40
MINIMAL	23	25	20

The experiment plan is a three-factor orthogonal plan 2^3 with one measurement at each point of the plan and with repeating measurements at the zero point of the plan four times in total (to reach the greater accuracy of the measured results), without taking into account the interaction of factors w , d , Q_{sp} .

The above mentioned plan, without taking into account the interaction of factors, with the planned order of conducting the experiments is shown in Table 2.

Table 2. Plan-matrix for performing experiments*

EXPER. POINT	LAND MASS w [%]	HOLE SIZE ON THE GRID d [mm]	SPECIFIC SUPPLY WITH LAND MASS Q_{sp} [kg/(s·m)]	PLAN-MATRIX			
				x_0	x_1	x_2	x_3
1	27	45	70	1	1	1	1
2	23	45	70	1	-1	1	1
3	27	25	70	1	1	-1	1
4	23	25	70	1	-1	-1	1
5	27	45	20	1	1	1	-1
6	23	45	20	1	-1	1	-1
7	27	25	20	1	1	-1	-1
8	23	25	20	1	-1	-1	-1
9	25	35	40	1	0	0	0
10	25	35	40	1	0	0	0
11	25	35	40	1	0	0	0
12	25	35	40	1	0	0	0

*Note: For the purpose of simplification of entering and processing of experimental data in the plan-matrix, proportions for the coordinate axes are selected so that the maximum (upper level) is equal to +1, the minimum (lower level) is equal to -1, and the middle (zero) level is equal to zero (0).

Figure 4 schematically shows three-factor orthogonal plan of experiments with four repetitions of measurement at the zero point of the plan.

Fig. 4. Three-factor orthogonal plan for performing the experiments

Basic experimental data:

$k=3$ - number of influential factors in experiment ($x_1 \equiv w$; $x_2 \equiv d$; $x_3 \equiv Q_{sp}$);

$n_o=4$ - number of repetitions of the measurement at the zero point of the plan;

$N_e = 2^k + n_o = 2^3 + 4 = 12$ - the total number of measurements (experiments).

3. CONDITIONS AND MODES OF RESEARCH AND MEASUREMENT RESULTS

The whole measurement was performed on an mono-grid experimental platform mounted on vibratory potato harvester type VWK-10 (Fig. 1).

The aim of the planned experiment is not to test digging or transporting capability of platform. Instead, it aims at testing its capabilities in regard to separation and sieving. For that reason, in order to facilitate measurement of the influential parameters, the land mass has not been excavated using the plowshare, but it is unloaded directly on the platform from tractor trailer using troughs (funnel).

On the trailer the land mass is watered using a hose in order to achieve the required moisture content w , which is measured on the spot using the apparatus owned by the Faculty of Agronomy in Cacak.

Land mass is previously unloaded on tractor trailer from plastic barrels whose mass is firstly measured on the scales. The velocity of unloading land mass from the trailer, i.e. velocity of supplying the platform with land mass is controlled using a stopwatch. At the same time, land mass is unloaded over the entire surface of grid as uniformly as possible in order to ensure required specific supply with land mass Q_{sp} [kg/(s·m)].

A third influential parameter, the hole size on the grid (d), is varied so that the steel strips are moved from each other at the required distance and then fixed to the new position with the threaded pins. This is possible thanks to the fact that there are beforehand drilled holes in carrier frame (position 6 in Fig. 1) into which threaded pins are mounted.

In order to correctly determine the mass of the sieved land mass during the experiment, the sheet metal plate is mounted below the platform grid (which is stationary) before the measurement starts, so that sieved land mass falls on it. When the platform stops, sieved land mass is removed by shovels from sheet metal plate and loaded into plastic barrels whose mass is measured again on the scales. By dividing the measured mass of the sieved land mass (at the end of the experiment) by the measured mass of the supplied land mass (at the beginning of the experiment), the value of coefficient of completeness of separation η for each particular experimental point is obtained. The procedure must be repeated twelve times, for each experimental point separately.

According to the adopted plan of experiment (Table 2) all relevant factors: w , d , Q_{sp} are controlled and varied within limits from +1 to -1, and the measured values of coefficient of completeness of separation η for all twelve measurements are shown in Table 3.

Table 3. The measured values of the coefficient η during experiments

EXP. POINT	1	2	3	4	5	6	7	8	9	10	11	12
COEFFIC. η	14	58	6	48	16	60	10	50	25	24	26	22
$y_i = \ln(\eta)$	2.64	4.06	1.79	3.87	2.77	4.09	2.30	3.91	3.22	3.18	3.26	3.09

4. REGRESSION ANALYSIS

This analysis includes determination of the regression coefficients b_i , which gains the insight into the influence of some factors on the output function η . If the analysis provides the factors with insignificant coefficients, they are not taken into account in further consideration.

The sign of the regression coefficient b_i gives insight into the type of influence of given factor on the studied process, where the plus sign (+) indicates directly proportional effect on measured value η while minus sign (-) indicates inversely proportional effect on measured value η .

The general mathematical model without interaction of factors x_1, x_2, x_3 according to [13] has the following form:

$$y = b_o \cdot x_o + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 \quad (3)$$

The symbols in the equation (3) have the following meaning:

y – logarithmic value of the measured value;

b_o, b_1, b_2, b_3 – regression coefficients that are calculated by regression analysis.

To achieve a higher reliability of calculations, the total number of measurements of three-factor ($k=3$) orthogonal plan is increased by $n_o=4$ repetitions of the measurement at the zero point of the plan:

$$N_e = 2^k + n_o = 2^3 + 4 = 12 \quad (4)$$

Further analysis is done using matrix calculation [13] followed by regression coefficients (b_i):

$$b_o = (1/12) \cdot (38.18) = 3.182$$

$$b_1 = (1/8) \cdot (-6.43) = -0.804$$

$$b_2 = (1/8) \cdot (1.69) = 0.211$$

$$b_3 = (1/8) \cdot (-0.71) = -0.089 \quad (5)$$

The regression coefficients b_i are known, so it is possible to write a mathematical model in coded form:

$$y = b_o \cdot x_o + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 \quad (x_o=1)$$

$$y = 3.182 - 0.804 \cdot x_1 + 0.211 \cdot x_2 - 0.089 \cdot x_3 \quad (6)$$

5. DISPERSION ANALYSIS

Using the dispersion analysis it is possible to determine the significance of regression coefficients b_i , as well as the adequacy of the mathematical model. Complete dispersion analysis is performed gradually according to the methodology indicated in [13].

I) Number of degrees of freedom:

$$f_r = N_e - k - 1 = 12 - 3 - 1 = 8$$

$$f_e = n_o - 1 = 4 - 1 = 3$$

$$f_a = f_r - f_e = 8 - 3 = 5$$

$$(f_o = 1; f_1 = 1; f_2 = 1; f_3 = 1)$$

II) Sum of the squared values:

$$s_{bo} = N_e \cdot b_o^2 = 12 \cdot 3.182^2 = 121,5015$$

$$s_{b1} = N \cdot b_1^2 = 8 \cdot (-0.804)^2 = 5,1713$$

$$s_{b2} = N \cdot b_2^2 = 8 \cdot 0.211^2 = 0,3562$$

$$s_{b3} = N \cdot b_3^2 = 8 \cdot (-0.089)^2 = 0,0634$$

III) Residual sum:

$$s_r = \sum_{i=1}^{12} y_i^2 - \left(N_e \cdot b_o^2 + \sum_{i=1}^3 N \cdot b_i^2 \right)$$

$$s_r = \left(2,64^2 + 4,06^2 + 1,79^2 + 3,87^2 + 2,77^2 + 4,09^2 + 2,30^2 + 3,91^2 + 3,22^2 + 3,18^2 + 3,26^2 + 3,09^2 \right) - (121,5015 + 5,1713 + 0,3562 + 0,0634) = 0,1774$$

V) Error of experiment in the zero point of the plan:

$$\bar{y}_o = \frac{3,22 + 3,18 + 3,26 + 3,09}{4} = 3,1875$$

$$s_e = \sum_{i=1}^{12} (y_{oi} - \bar{y}_o)^2 = (3,22 - 3,1875)^2 + (3,18 - 3,1875)^2 + (3,26 - 3,1875)^2 + (3,09 - 3,1875)^2 = 0,0159$$

V) Adequate sum:

$$s_a = s_r - s_e = 0,1774 - 0,0159 = 0,1615$$

VI) Dispersions:

$$s_{bo}^2 = \frac{s_{bo}}{f_o} = \frac{121,5015}{1} = 121,5015$$

$$s_{b1}^2 = \frac{s_{b1}}{f_1} = \frac{5,1713}{1} = 5,1713$$

$$s_{b2}^2 = \frac{s_{b2}}{f_2} = \frac{0,3562}{1} = 0,3562$$

$$s_{b3}^2 = \frac{s_{b3}}{f_3} = \frac{0,0634}{1} = 0,0634$$

.....

$$s_r^2 = \frac{s_r}{f_r} = \frac{0,1774}{8} = 0,0222$$

$$s_e^2 = \frac{s_e}{f_e} = \frac{0,0159}{3} = 0,0053$$

$$s_a^2 = \frac{s_a}{f_a} = \frac{0,1615}{5} = 0,0323$$

VII) Determination of Fisher's "F-values":

$$F_{ro} = \frac{s_{bo}^2}{s_e^2} = \frac{121,5015}{0,0053} = 22924,8;$$

$$F_{r1} = \frac{s_{b1}^2}{s_e^2} = \frac{5,1713}{0,0053} = 975,7;$$

$$F_{r2} = \frac{s_{b2}^2}{s_e^2} = \frac{0,3562}{0,0053} = 67,2;$$

$$F_{r3} = \frac{s_{b3}^2}{s_e^2} = \frac{0,0634}{0,0053} = 11,96;$$

$$F_{ra} = \frac{s_a^2}{s_e^2} = \frac{0,0323}{0,0053} = 6,1;$$

VIII) The significance of regression coefficients:

Fisher's "F-test" is applied to determine the significance of the regression coefficients, where the coefficient of risk is adopted as 5% ($\alpha=0.05$).

$$F_t(\alpha, f_i, f_e) = F_t(0.05; 1; 3) = 10.13 \text{ (acc. to [13])}.$$

Each calculated value of Fisher's "F-values" is compared with the value F_t , i.e. it is checked whether the necessary condition is fulfilled for each particular case:

$$F_{ri} > F_t \quad (7)$$

$$F_{ro} > F_t; \quad F_{rl} > F_t; \quad F_{r2} > F_t; \quad F_{r3} > F_t \quad (8)$$

From (8) it can be noted that the necessary condition (7) is fulfilled in the case of all coefficients, which means that all the regression coefficients: b_o, b_1, b_2, b_3 are significant with a risk of 5%, i.e. they are quite justifiably written into the regression equation (6) which is a coded form of the mathematical model.

IX) Adequacy of the mathematical model:

Fisher's "F-test" can also be applied here by adopting the coefficient of risk of 5% ($\alpha=0.05$).

$$F_t(\alpha, f_a, f_e) = F_t(0.05; 5; 3) = 9.01 \text{ (acc. to [13])}.$$

In this case it is necessary to fulfill the following condition:

$$F_{ra} < F_t \quad (9)$$

$$(F_{ra}=6.1) < (F_t=9.01) \quad (10)$$

From equation (10) it can be noticed that the necessary condition (9) is fulfilled, which means that the obtained mathematical model completely describes the studied problem of separation and sieving of wet land mass on the oscillatory platform. Therefore, this model is adequate, having in mind that the coefficient of risk for this statement is previously adopted 5% ($\alpha=0.05$).

6. DECODING OF MATHEMATICAL MODEL

Mathematical model in decoded form has the following form [13]:

$$y = B_o \cdot x_1^{\beta_1} \cdot x_2^{\beta_2} \cdot x_3^{\beta_3} \quad (11)$$

The levels of input variables:

$$x_{1max}=27; \quad x_{2max}=45; \quad x_{3max}=70;$$

$$x_{1min}=23; \quad x_{2min}=25; \quad x_{3min}=20;$$

Coefficient B_o is calculated according to the formula:

$$B_o = e^{\beta_0} \quad (12)$$

The exponent in the equation (12) is calculated according to the formula:

$$\beta_o = b_o + b_1 \cdot a_1 + b_2 \cdot a_2 + b_3 \cdot a_3 \quad (13)$$

In the equation (13) coefficients a_i ($i=1, 2, 3$) are calculated as follows:

$$a_1 = 1 - A_1 \cdot \ln(x_{1max}) = 1 - 12,47 \cdot \ln 27 = -40,099$$

$$a_2 = 1 - A_2 \cdot \ln(x_{2max}) = 1 - 3,40 \cdot \ln 45 = -11,943$$

$$a_3 = 1 - A_3 \cdot \ln(x_{3max}) = 1 - 1,60 \cdot \ln 70 = -5,798$$

Coefficients A_i ($i=1, 2, 3$) have the following values:

$$A_1 = \frac{2}{\ln \frac{x_{1max}}{x_{1min}}} = \frac{2}{\ln \frac{27}{23}} = 12,47$$

$$A_2 = \frac{2}{\ln \frac{x_{2max}}{x_{2min}}} = \frac{2}{\ln \frac{45}{25}} = 3,40$$

$$A_3 = \frac{2}{\ln \frac{x_{3max}}{x_{3min}}} = \frac{2}{\ln \frac{70}{20}} = 1,60$$

By substituting coefficients a_1, a_2, a_3 and previously calculated regression coefficients b_o, b_1, b_2 , and b_3 into equation (13), we get the following value:

$$\begin{aligned} \beta_o = & 3,182 + (-0,804) \cdot (-40,099) + 0,211 \cdot (-11,943) + \\ & + (-0,089) \cdot (-5,798) = 33,418 \end{aligned}$$

By substituting exponent β_o in (12), the following value is obtained:

$$B_o = e^{33,418} = 3,26 \cdot 10^{14}$$

Now it is possible to calculate values of all other exponents:

$$\beta_1 = A_1 \cdot b_1 = 12,47 \cdot (-0,804) = -10,03$$

$$\beta_2 = A_2 \cdot b_2 = 3,40 \cdot 0,211 = 0,72$$

$$\beta_3 = A_3 \cdot b_3 = 1,60 \cdot (-0,089) = -0,14$$

By substituting all calculated values into equation (11), the final value of the mathematical model is obtained in decoded form:

$$\begin{aligned} y = & 3,26 \cdot 10^{14} \cdot x_1^{-10,03} \cdot x_2^{0,72} \cdot x_3^{-0,14} \\ y = & 3,26 \cdot 10^{14} \cdot \frac{x_2^{0,72}}{x_1^{10,03} \cdot x_3^{0,14}} \end{aligned} \quad (14)$$

Keeping in mind that: $y \equiv \eta$, $x_1 \equiv w$, $x_2 \equiv d$, $x_3 \equiv Q_{sp}$, equation (14) can be written in the final form that represents the experimentally obtained mathematical model of the process of separation and sieving of wet land mass on the oscillatory platform:

$$\eta = 3,26 \cdot 10^{14} \cdot \frac{d^{0,72}}{w^{10,03} \cdot Q_{sp}^{0,14}} \quad (15)$$

7. ANALYSIS OF EXPERIMENTAL RESULTS

From the experimentally obtained mathematical model (15) it is evident that the bigger the hole size on the grid ($d \uparrow$), the greater the coefficient of completeness of separation ($\eta \uparrow$), which means there is a direct proportionality.

Contrary to that, the greater the land mass moisture ($w \uparrow$) and the greater the specific supply with land mass ($Q_{sp} \uparrow$), the lower the coefficient of completeness of separation ($\eta \downarrow$), which means that the above mentioned factors are reversely proportional.

Thus, according to tables T.2 and T.3 the maximum value of coefficient of completeness of separation is obtained in the experimental point 6 ($\eta=60\%$, for $w_{min}=23\%$, $d_{max}=45mm$, $Q_{spmin}=20kg/(s \cdot m)$), while the minimum value of coefficient of completeness of separation is obtained in the experimental point 3 ($\eta=6\%$, for $w_{max}=27\%$, $d_{min}=25mm$, $Q_{spmax}=70kg/(s \cdot m)$).

By comparing the values of the exponents in (15) it can be concluded that land mass moisture has the greatest influence on coefficient of completeness of separation η ($|\beta_1|=10.03$); hole size on the grid has significantly less influence ($|\beta_2|=0.72$); and specific supply with land mass has the least significant effect ($|\beta_3|=0.14$). Therefore, the aforementioned influences can be presented by the following inequation:

$$|\beta_1| > |\beta_2| > |\beta_3| \quad (16)$$

If inequation (16) is analyzed once again, it can be noted that the specific supply with land mass Q_{sp} is the least influential factor on the separation and sieving of wet land mass (because the exponent is $|\beta_3|=0.14$). The next factor according to the rank of significance is the hole size on the grid d (the exponent is $|\beta_2|=0.72$), and the most influential factor is land mass moisture w (the exponent is $|\beta_1|=10.03$).

For this reason, in order to facilitate and simplify the graphical presentation, it is possible to simplify and assume that $Q_{sp} \approx \text{const}$, while the other two influential factors, land mass moisture and hole size on the grid, are treated as variables ($w \neq \text{const}$, $d \neq \text{const}$).

A graphical representation of the optimization of parameters influencing the separation and sieving of wet land mass is shown in Fig. 5.

Fig 5. Optimization of working parameters influencing the separation and sieving of wet land mass by means of oscillatory platform

8. CONCLUSION

Sieving of wet materials using machines and devices with built-in oscillating platforms is a very complex process which requires a multidisciplinary approach [14].

Due to the numerous limitations in counterposition and due to the relatively large number of influencing factors, the aforementioned task should be treated as a kind of optimization process. Fulfillment of one optimization criterium can often lead to a failure to fulfill other criterium, so the final solution, as always in similar situations, must represent a compromise.

Therefore, the following concrete conclusions on fineness of separation of wet land mass can be made:

- **Conclusion 1:** Land mass moisture w is the most influential factor on coefficient of completeness of separation η ($|\beta_1|=10.03$ according to (15)), so if $w > 27\%$ the operation of oscillating platform becomes totally ineffective and inadvisable due to the drastic decline in its productivity. No other constructional changes can contribute much to improve the work of platform in such difficult working conditions.

- **Conclusion 2:** The hole size on the grid d is the factor which is approximately 14 times less influential on the fineness of separation η than land mass moisture w ($|\beta_2|=0.72$ according to (15)), so if increased it is influential only if moisture is up to $w \approx 25\%$. Beyond this value of moisture, η does not increase even if there is a noticeably increase of the hole size on the grid.

- **Conclusion 3:** Specific supply with land mass Q_{sp} is the least influential factor on the fineness of separation η ($|\beta_3|=0.14$ according to (15)) and its increase above the upper limit may cause self-unloading of land mass and significant reduction of coefficient η . In practice, it is necessary to determine the optimal unloading value of the specific supply factor Q_{sp} of each machine with built-in oscillatory platform by means of experiments first and then to prescribe it, too.

• **Conclusion 4:** Due to the fact that all three abovementioned influential factors (w , d , Q_{sp}) are really significant factors, and due to experimentally proven adequacy of the mathematical model, the assumption given by equation (2) can be fully accepted, with a coefficient of risk of 5% according to Fisher's "F"-criterion which is one of the most accepted criteria in mathematical statistics.

Therefore, it can be concluded that the optimization of influential parameters is very important for achieving maximum productivity of oscillatory platforms for sieving and separation of wet land mass [15]. Nowadays, transportation machines and devices must provide high safety, reliability and stability even in the most difficult operating conditions, so it is necessary to meet all these requirements at the design stage. This is the only guarantee that the platform machines will function properly in the real exploitation conditions to the satisfaction of both manufacturers and users of the machines and devices.

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