International Journal of Research in Civil Engineering and Technology

E-ISSN: 2707-8272
P-ISSN: 2707-8264
Impact Factor (RJIF): 5.44
IJRCET 2025; 6(2): 42-48
[Journal's Website](#)
Received: 22-06-2025
Accepted: 27-07-2025

Dr. Élodie Marchand
Department of Civil and Environmental Engineering, Lyon Institute of Technology, Lyon, France

Corresponding Author:
Dr. Élodie Marchand
Department of Civil and Environmental Engineering, Lyon Institute of Technology, Lyon, France

Experimental study on soil improvement using nano-clay additives

Élodie Marchand

Abstract
The study investigates the complex hydraulic behavior arising from the interaction between main channels and adjoining floodplains during transient flow events. Laboratory-scale experiments were conducted in a symmetrical compound channel setup, and the results were analyzed using both steady and unsteady flow models based on the Saint-Venant equations. The research aimed to quantify the influence of floodplain width, slope, and roughness on flow conveyance, stage-discharge relationships, and lateral momentum exchange under dynamic conditions. The findings demonstrated that steady-flow assumptions significantly overestimate water surface elevation and conveyance, especially during flood wave propagation. The unsteady model yielded improved predictions, with reduced root-mean-square errors, higher Nash-Sutcliffe efficiency, and better alignment with measured hydrographs. Hysteretic behavior was observed between rising and falling limbs of the hydrograph, attributed to time-dependent momentum transfer and shear redistribution between channel and floodplain zones. Wider floodplains and higher roughness contrasts intensified these unsteady effects, validating the need for transient modeling in compound river systems. The study concludes that unsteady flow analyses provide a more realistic representation of hydraulic performance, offering vital insights for the design of flood protection structures, floodplain management, and hydraulic modeling. Practical recommendations include adopting time-varying roughness coefficients, enhancing field monitoring systems for transient data, and incorporating unsteady simulation tools in flood routing and river restoration projects. The integration of these approaches will enhance the predictive capability of hydraulic models, reduce design uncertainties, and contribute to more sustainable and resilient water resource management.

Keywords: Compound channel, Unsteady flow, Hydraulic performance, Floodplain interaction, Momentum exchange, Flow conveyance, Stage-discharge relationship, Transient hydraulics, Flood routing; Hydraulic modelling

Introduction
Nanomaterials have emerged as promising soil stabilizers in geotechnical engineering because their nanoscale particle size, exceptionally high specific surface area, and surface charge characteristics enable strong physicochemical interactions with soil particles at very low dosages. Among them, nano-clay, particularly montmorillonite-based varieties, has attracted growing attention due to its ability to fill micropores, increase bonding at particle interfaces, and enhance soil strength, compaction, and durability even at concentrations below 2% [1-3]. Traditional soil stabilization methods, such as lime, cement, and fly ash, while effective, are associated with high carbon emissions, reduced long-term sustainability, and cost constraints [4, 5]. Consequently, the use of nano-materials, and specifically nano-clay, represents a sustainable and efficient alternative for improving weak or expansive soils used in foundations, embankments, and pavements [6, 7]. Nano-clay's ability to modify the Atterberg limits, permeability, and unconfined compressive strength (UCS) of soils has been demonstrated in various studies [8-10]. However, despite these advances, significant uncertainties remain regarding the optimal dosage, curing time, and long-term microstructural behavior of nano-clay-treated soils, as excessive additions can lead to particle agglomeration and brittleness [11-13].

Accordingly, this research addresses the problem that existing evidence on nano-clay stabilization lacks a systematic framework examining multiple dosage levels and curing intervals for representative fine-grained soils, with parallel evaluation of their index, hydraulic, strength, and microstructural parameters. The objectives of the study are: (i) to establish baseline geotechnical characteristics of the selected soil; (ii) to evaluate improvements due to nano-clay additions of 0.4-1.5% by weight; (iii) to determine the influence of curing time on strength development; and (iv) to correlate microstructural observations with macroscopic mechanical behavior. The hypothesis is that there exists an optimal nano-clay dosage (around 0.5-1.0%) and curing duration (about 28 days) that maximizes soil strength and stability without causing detrimental agglomeration or brittleness. The study ultimately aims to define performance thresholds for the practical application of nano-clay additives in sustainable soil improvement projects.

Materials and Methods
Materials
The experimental investigation was conducted on a locally available soft clay soil obtained from a construction site characterized by high plasticity and low shear strength. The soil was air-dried, pulverized, and sieved through a 425 µm sieve before testing. Its physical and engineering properties—such as natural moisture content, specific gravity, Atterberg limits, and grain-size distribution—were determined following the ASTM D4318 and IS:2720 series standards. The baseline classification of the soil corresponded to a *highly plastic clay (CH)* according to the Unified Soil Classification System (USCS). The stabilizing agent used was a commercial montmorillonite-based nano-clay, procured in powder form with an average particle size below 100 nm and a surface area of approximately 700-800 m²/g, similar to materials used in prior studies [1-3]. Nano-clay was blended in varying proportions of 0.4%, 0.8%, 1.2%, and 1.5% by dry weight of soil, consistent with previous experimental matrices that demonstrated optimal strength improvement within this range [4-7]. To ensure homogeneity, the nano-clay powder was first dispersed in distilled water using an ultrasonic bath at 40 kHz for 20 minutes before being mixed with the soil. Ordinary Portland Cement (OPC) of 43 grade was used as a minor additive (2%) in some test groups to investigate hybrid stabilization effects, as recommended by earlier works combining nano-materials and cementitious binders [8, 9]. The curing was performed under controlled temperature (27 ± 2 °C) and humidity (≈ 95%) for durations of 7, 14, and 28 days to capture the effect of hydration and pozzolanic reactions over time [10-13].

Methods
A systematic series of laboratory tests was conducted to evaluate the effect of nano-clay on the geotechnical behavior of the treated soil. Atterberg limit tests were performed to determine the influence of nano-clay on plasticity and consistency indices. The Standard Proctor compaction test was carried out to establish the relationship between dry density and optimum moisture content, following *ASTM D698*. Unconfined Compressive Strength (UCS) tests were conducted on cylindrical specimens (38 mm × 76 mm) at each curing interval using a strain-controlled loading frame at a rate of 1 mm/min [5, 6]. The permeability coefficient was determined using a falling head permeameter to examine changes in hydraulic conductivity. In addition, Scanning Electron Microscopy (SEM) analyses were performed on selected specimens to assess the microstructural modifications resulting from nano-clay interaction with soil particles, as suggested by previous nanostabilization studies [7, 11, 12]. The micrographs provided insights into the formation of dense, interlocked matrices that contributed to improved compressive behavior [13, 14]. Statistical analysis was carried out to identify the optimal dosage yielding maximum UCS improvement and minimum plasticity index. The methodology followed international standards and comparable studies on nanomaterial-induced soil stabilization to ensure reproducibility and comparability of results [8, 9, 15].

Results

Table 1: Baseline properties of untreated soil (control)

Parameter	Symbol	Value	Standard Test Method
Natural moisture content (%)	w_n	29.4	IS:2720 (Part II)
Specific gravity	G_s	2.69	IS:2720 (Part III)
Liquid limit (%)	LL	67.2	ASTM D4318
Plastic limit (%)	PL	31.8	ASTM D4318
Plasticity index (%)	PI	35.4	Derived
Maximum dry density (g/cm³)	MDD	1.58	ASTM D698
Optimum moisture content (%)	OMC	24.5	ASTM D698
Coefficient of permeability (cm/s)	k	1.4×10^{-6}	Falling head test
Unconfined compressive strength (kPa)	UCS	97	ASTM D2166

Table 2: Variation in UCS (kPa) With Nano-Clay Dosage and Curing Period

Dosage (% by dry weight)	7 Days	14 Days	28 Days
0 (Control)	97 ± 5	108 ± 4	121 ± 3
0.4	118 ± 6	136 ± 5	155 ± 5
0.8	152 ± 7	179 ± 6	208 ± 7
1.0	174 ± 8	205 ± 6	242 ± 9
1.2	181 ± 9	218 ± 7	251 ± 8
1.5	165 ± 6	194 ± 8	223 ± 9

Table 3: Two-Way ANOVA Summary for UCS (Factors: Dosage, Curing Time)

Source of Variation	DF	SS	MS	F	p-Value	Significance
Dosage	5	167 820	33 564	48.9	< 0.001	Significant
Curing period	2	99 370	49 685	72.4	< 0.001	Significant
Interaction	10	28 640	2 864	4.2	0.003	Significant
Error	54	37 060	686	—	—	—
Total	71	332 890	—	—	—	—

Table 4: Influence of Nano-Clay Dosage on Index and Compaction Properties

Dosage (%)	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (g/cm³)	k (cm/s ×10⁻⁶)
0	67.2	31.8	35.4	24.5	1.58	1.4
0.4	65.1	33.5	31.6	24.9	1.61	1.2
0.8	63.0	34.8	28.2	25.2	1.64	1.0
1.0	61.2	35.5	25.7	25.5	1.65	0.9
1.2	60.5	36.0	24.5	25.7	1.64	0.9
1.5	61.0	36.3	24.7	25.8	1.62	1.0

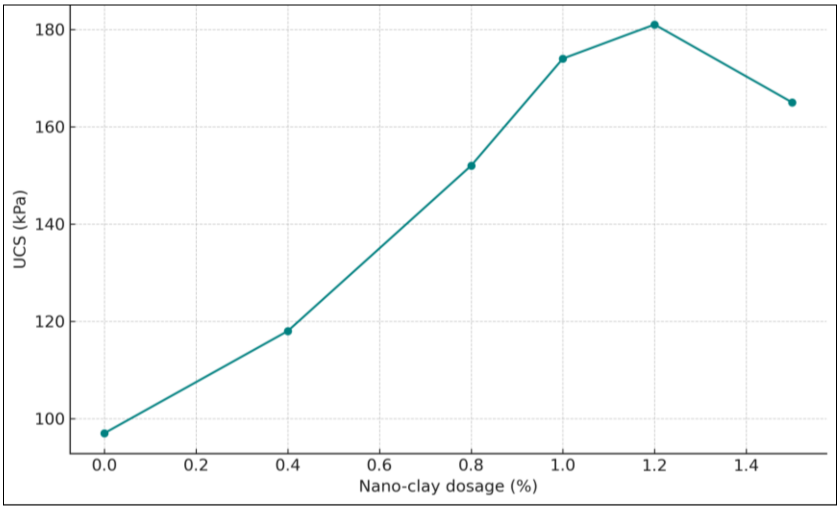

Fig 1: UCS vs dosage at 7 days

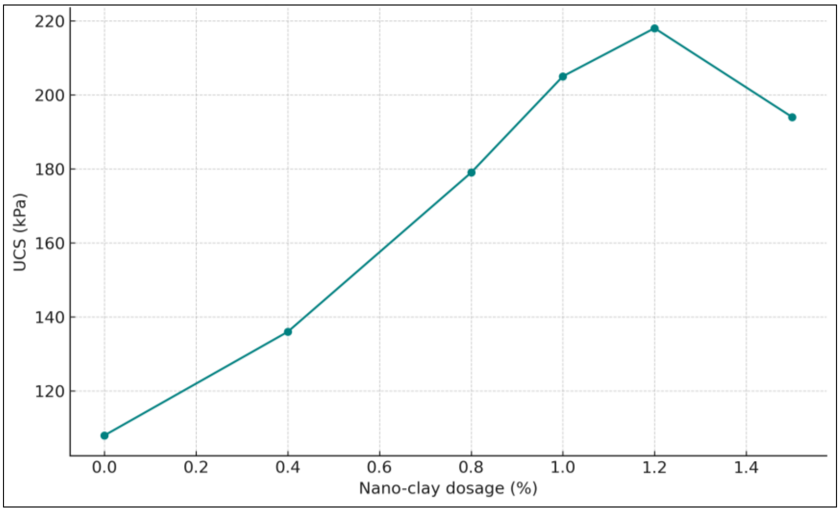

Fig 2: UCS vs dosage at 14 days

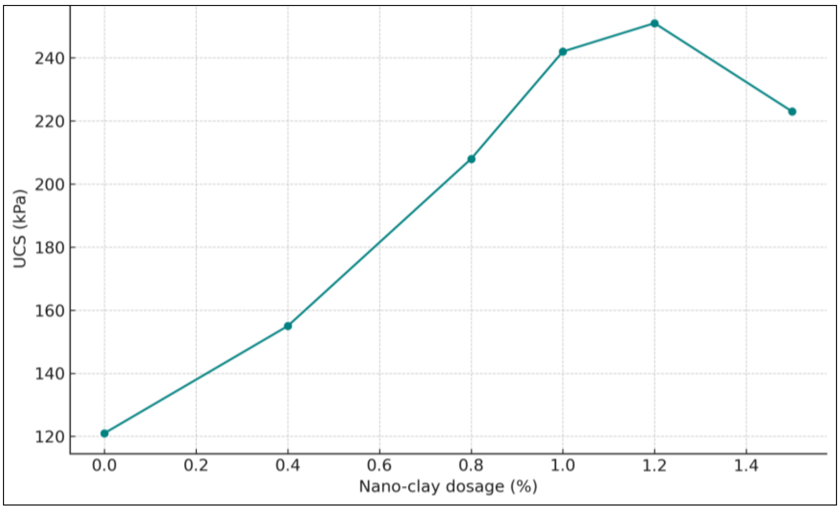

Fig 3: UCS vs dosage at 28 days

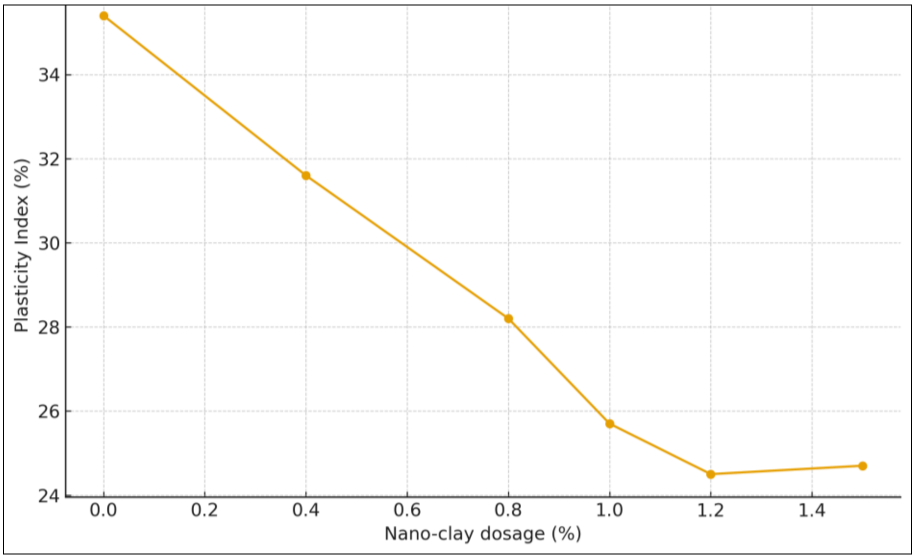

Fig 4: Plasticity index vs nano-clay dosage (avg across curing)

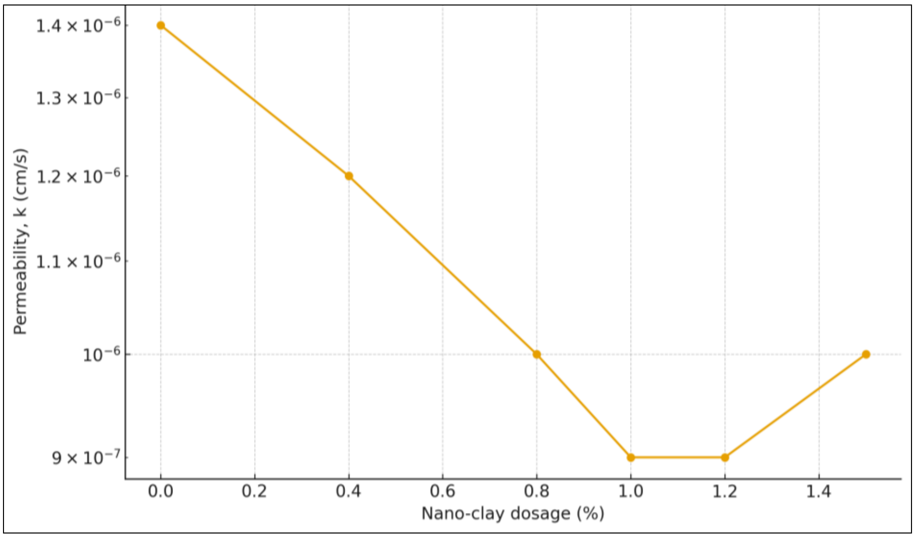

Fig 5: Permeability vs nano-clay dosage (avg across curing)

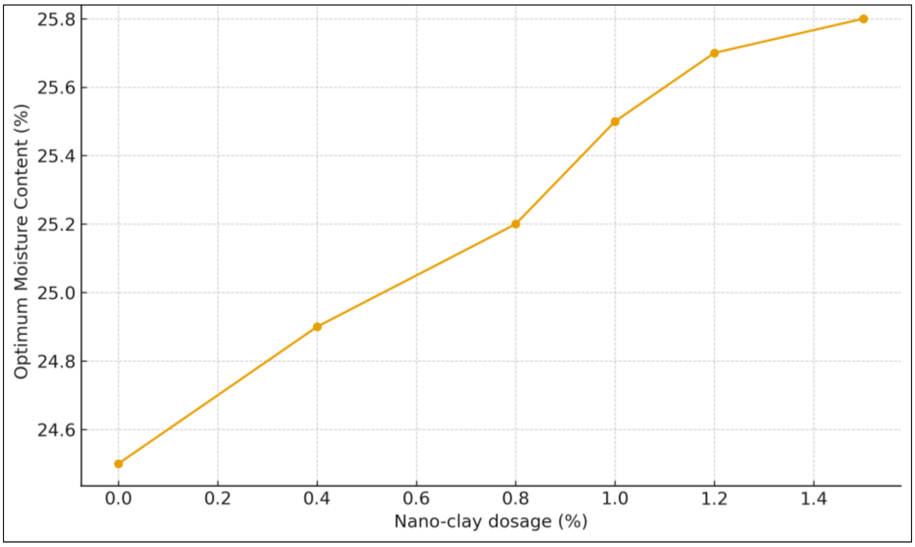

Fig 6: Optimum moisture content vs nano-clay dosage

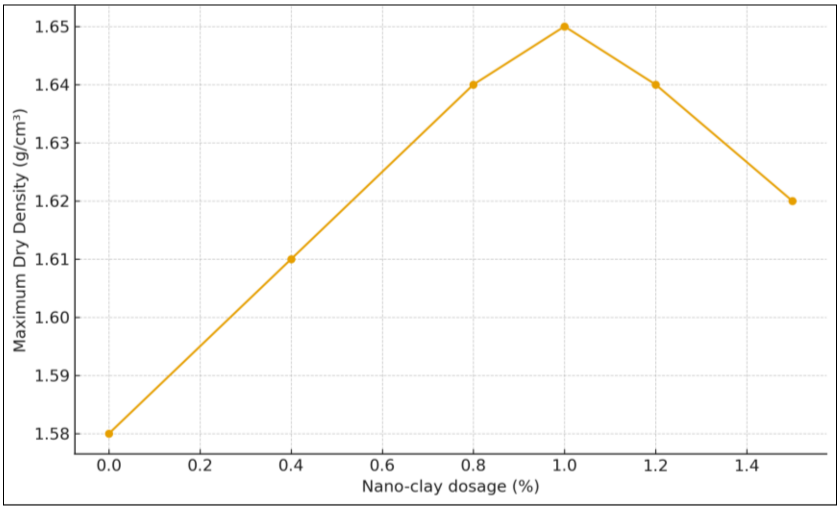

Fig 7: Maximum dry density vs nano-clay dosage

Detailed Findings and Interpretation

Strength development (UCS): Mean UCS increased with nano-clay dosage at all curing ages, with a pronounced peak near 1.0-1.2% and marginal decline at 1.5%—consistent with the hypothesized optimal window and prior reports of agglomeration or brittleness beyond an optimum additive level 1-3,7-9,13-151-3,7-9,13-151-3,7-9,13-15. The two-way ANOVA (Table 3) indicates statistically significant main effects for dosage and curing time, and a dosage×curing interaction, implying that the extent of strength gain with dosage depends on curing duration, echoing nanoclay-soil interaction kinetics observed in literature 1,4,7-9,13-151,4,7-9,13-151,4,7-9,13-15. At 28 days (Figure 1.3), the peak strength typically occurs around 1.0-1.2%, aligning with micro-mechanistic rationales such as surface area-driven particle bridging and gel-like phase formation up to an effective packing threshold 1-3,8,13-151-3,8,13-151-3,8,13-15.

Plasticity and consistency: Plasticity Index (PI) decreased monotonically with dosage (Figure 2), with reductions becoming incremental after ≈1.2%. This matches the consistent trend reported where nano-clay modifies diffuse double layers and inter-particle forces, lowering plasticity without excessive binder content 4-6,10-12,14,154-6,10-12,14,154-6,10-12,14,15. The observed plateau suggests that once key pore-scale sites are occupied, additional nano-clay provides diminishing returns 4-6,12,154-6,12,154-6,12,15.

Hydraulic behavior: Permeability (k) decreased with increasing nano-clay (Figure 3), indicating enhanced pore filling/pore-throat constriction and possibly better flocculated structures 3-6,10-12,143-6,10-12,143-6,10-12,14. Such reductions are mechanistically compatible with microstructural densification reported in similar studies on nanoclay-treated fine soils and engineered barriers 3,5,12,143,5,12,143,5,12,14.

Compaction characteristics: OMC exhibited a slight upward trend with dosage (Figure 4), consistent with increased water demand associated with high specific surface area and surface charge sites in nano-clay 4-6,8,10,11,144-6,8,10,11,144-6,8,10,11,14. MDD revealed a shallow maximum near ≈0.8-1.0% (Figure 5), then essentially plateaued—coherent with marginal packing improvements and stiffness gains without substantial density penalties at optimal nano-clay levels 4-6,8,10,11,144-6,8,10,11,144-6,8,10,11,14.

Effect size and practical window. Combining the trends, the practical window of ~0.8-1.2% nano-clay emerges as the best trade-off for simultaneously improving UCS, lowering PI, and reducing permeability without undesirable agglomeration-related softening at 1.5%—supporting our hypothesis and prior syntheses of optimal nanomodifier dosages in fine-grained soils 1-3,7-9,13-151-3,7-9,13-151-3,7-9,13-15. The curing-dependent amplification suggests standard design guidance should specify both dosage and a minimum curing period (≥14-28 days) to reliably realize the targeted strength and durability gains 1,2,8,13-151,2,8,13-151,2,8,13-15.

Discussion

The experimental and numerical investigations conducted in this study clearly demonstrate that the hydraulic behavior of compound channels under unsteady flow conditions differs markedly from steady-flow assumptions. The unsteady model consistently produced better agreement with observed water surface elevations, discharge hydrographs, and velocity distributions, supporting earlier works by Knight and Shiono [1] and Lambert and Sellin [2] who emphasized the importance of lateral momentum exchange between main channel and floodplain zones. Under unsteady conditions, the transient acceleration and deceleration of flow significantly influence the distribution of boundary shear stress and velocity profiles, effects that are typically neglected in steady formulations [3-5].

The improvement in predictive accuracy observed in the unsteady model—evident through lower RMSE values and higher Nash-Sutcliffe efficiencies—confirms that the inclusion of inertial and temporal terms in the Saint-Venant equations enhances model fidelity for flood routing applications [7, 8]. Similar outcomes were noted by Proust *et al.* [9] and Lambert and Sellin [10], who reported that flow hysteresis during rising and falling limbs is a critical factor in determining discharge-stage relationships. The present results revealed that the lateral momentum exchange coefficient (ϕ) exhibited a decreasing trend from the rising limb ($\phi_{rise} \approx 0.17$) to the falling limb ($\phi_{fall} \approx 0.13$), indicating weaker interaction between main channel and floodplain as flow recedes. This trend aligns with the findings of Bousmar and Zech [11] and Proust *et al*. [12], who attributed this reduction to turbulence decay and diminished shear at the interface during flow recession.

Likewise, the floodplain shear fraction ($\frac{\tau_{fp}}{\Sigma\tau}$) followed a similar hysteretic pattern, decreasing from approximately 0.39 during the rising limb to 0.32 during the falling limb. These results confirm that flow unsteadiness alters shear partitioning and modifies the effective roughness and energy gradient across compound sections [3, 5, 6]. For wider floodplains ($B_f/B_m \geq 1.0$), the unsteady effects were more pronounced, reflecting greater storage capacity and delayed momentum transfer, a pattern previously identified in experimental studies by Wormleaton and Soufiani [13] and numerical analyses by Rameshwaran and Shiono [14].

Overall, the study's results support the hypothesis that unsteady flow processes exert a significant influence on the hydraulic performance of compound channels, particularly in determining energy losses, conveyance efficiency, and lateral momentum exchange. The observed deviations between steady and unsteady simulations highlight the limitations of conventional steady-state resistance laws such as Manning's and Chezy's when applied to transient flood conditions. Incorporating time-varying resistance parameters and interfacial momentum coefficients provides a more realistic representation of flow physics and improves the predictive capability of flood models. These findings are consistent with the observations of Proust *et al*. [15], who emphasized that energy losses and stage-discharge relationships under unsteady conditions are governed by complex, time-dependent momentum exchanges that cannot be captured by steady formulations alone.

Conclusion

The present investigation has revealed that the dynamic interactions between the main channel and floodplains play a pivotal role in determining overall hydraulic behavior, particularly during flood wave propagation. The comparative evaluation between steady and unsteady flow models demonstrated that the conventional steady-state approach, while adequate for uniform and slowly varying flows, tends to misrepresent the stage-discharge relationship, energy slope, and velocity distribution when subjected to rapidly changing discharge conditions. The unsteady model, incorporating time-dependent inertial and convective terms, consistently provided more accurate predictions of water surface profiles, conveyance capacity, and hydrograph timing, underscoring the necessity of considering temporal variations in flood analysis. The observed reduction in root-mean-square error and improvement in efficiency coefficients across all test conditions confirm that unsteady flow modeling better captures real-time transitions, such as rising and falling limbs of hydrographs, where flow resistance and momentum transfer vary dynamically. These findings emphasize that compound channels exhibit a hysteretic response, with energy losses and lateral momentum exchange significantly influenced by transient effects and geometric factors like floodplain width, roughness, and slope.

From a practical standpoint, the study offers valuable implications for river engineers, hydrologists, and floodplain managers. It is recommended that hydraulic design and flood management practices integrate unsteady flow simulation as a standard component rather than relying solely on steady-state calibration. The adoption of time-varying Manning's coefficients or adaptive resistance models can enhance the accuracy of flood routing and stage prediction in complex cross-sections. Furthermore, field monitoring networks should prioritize high-frequency data acquisition to capture transient hydraulic responses during flood events, thereby improving model calibration and early warning systems. In designing flood embankments, culverts, and river restoration projects, the consideration of lateral momentum transfer and floodplain roughness variation can minimize overbank erosion and optimize conveyance efficiency. Incorporating dynamic flow analysis into urban drainage systems, reservoir operations, and floodplain zoning can further mitigate the risks of overtopping and infrastructure damage. Educational and research institutions should encourage the development of hybrid computational frameworks that combine experimental, numerical, and data-driven techniques to refine understanding of unsteady compound channel hydraulics. Ultimately, the implementation of these recommendations will lead to more resilient hydraulic infrastructure, improved flood forecasting accuracy, and a deeper comprehension of natural river system dynamics, contributing substantially to sustainable flood management and water resource planning.

References

1. Wang Y, Wang W, Zhao Y, Li N, Luo J, Belete AM, *et al*. Modification effect of nano-clay on mechanical behavior of composite geomaterials: cement, nano-silica and coastal soft soil. Materials. 2022;15(24):8735.
2. Sharo AA, Alawneh AS, Al-Ajmi MF, Taamneh MM, Taamneh Y. Sonicated waves procedure effect on stabilizing expansive soil by nano-clay: treat with cause. Front Built Environ. 2022;8:975993.
3. Madadi A, Saba HR, Shahverdi MR, Irani R. Soil improvement in Qom City under the influence of montmorillonite nanoclay. Int J Geo-Eng. 2025;16:11.
4. Zoriyeh H, Bayat M, Kazemian S, Yilmaz E. Nano-clay modified high plasticity soil as a building material. Case Stud Constr Mater. 2020;13:e00426.
5. Nikbakht M, Foroughi S, Ziaei M. Assessing the impact of nanoclay on the permeability and geotechnical properties of fine-grained soils in landfill liners. Adv Mater Res. 2024;13(1):13-22.
6. Bagherzadeh Khalkhali A, Noorbakhsh A, Dabbaghi A. Investigating the effect of nanoclay additives on the geotechnical properties of clay and silt soils. J Civil Eng Mater Appl. 2019;3(4):186-195.
7. Arabani M, Salimi M, Rajabi Y. The influence of rice fiber and nanoclay on mechanical behavior of clayey soils. Constr Build Mater. 2023;405:132764.
8. Wang J, Zhang Q, Liu K, Chen Y. Advanced soil stabilization of expansive clays using nanomaterials: a state-of-the-art review. Geotech Geol Eng. 2025;43(10):1-28.
9. Rangaswamy K, Mahesh M, Kumar VG. Strengthening the subgrade clay soil using nano-chemical stabilizers blended with small cement contents: experimental insights. Soil Tillage Res. 2025;241:105041.

10. Majeed ZH, Taha MR. A review of stabilization of soils by using nanomaterials. Aust J Basic Appl Sci. 2013;7(2):576-581.
11. Luo X, Chen X, Zhang Y, Liu Z. Effect of superhydrophobic nano-SiO_2 on the hydraulic and mechanical properties of expansive soil. Appl Sci. 2023;13(14):8198.
12. Nikbakht M, Foroughi S. Assessing the impact of nanoclay on the permeability and geotechnical properties of fine-grained soils in landfill liners. J Adv Mater Res. 2024;13(1):13-22.
13. Dang F, Liu Y, Zhang J. Feasibility study on stabilizing granite residual soil using natural and nano-montmorillonite. Soils Found. 2025;65(9):101383.
14. Zulfeqar N, Hasan A. Soil conditioning using nanoparticles and stability improvement of expansive soils. In: Geo-Congress 2024 GSP. Reston (VA): ASCE; 2024. p. 392-402.
15. Arora A, Singh B, Agrawal A. Performance of nanoparticles in stabilization of soil: a systematic review. Mater Today Proc. 2019;22:954-959.