Analysis and design of auto-adaptive leveling hydraulic suspension for agricultural robot

Kai Hu, Wenyi Zhang and Bing Qi

Abstract
The application of agricultural robot in hilly and mountainous areas faces several problems, such as bad walking performance, easy tilt, and low safety. The auto-adaptive leveling hydraulic suspension for the agricultural robot can help to eliminate some sort of problems. The design of such system is the main aim of the article. The hydraulic system with load-sensing system and its controlling model were established and then the load-sensing system was modeled and simulated in Advanced Modeling Environment for SIMulation. The optimal proportional–integral–derivative parameters were determined by the optimized algorithm. The simulation results illustrated that the inlet and outlet pressure difference of throttle and the flow rate through throttle are 42 bar and 29.65 L/min, respectively, all the time when the load pressure varies from 0 bar to 100 bar. The load-sensing system has good power follow-up and high control accuracy. And then the experimental bench of auto-adaptive leveling hydraulic suspension was researched and developed to verify the leveling performance. The experimental results demonstrate that auto-adaptive leveling hydraulic suspension can keep frame leveling dynamically on upslope, downslope, side slope, and continuous undulating road surface. The maximum errors of the pitch angle and the tilt angle are $-0.93^\circ$ and $0.97^\circ$. The feasibility of the designed hydraulic suspension was verified. The research methods in this article can provide theoretical basis for the design of other auto-adaptive leveling systems in hilly and mountainous areas.

Keywords
Hilly and mountainous areas, auto-adaptive leveling, hydraulic suspension, load-sensing system, controlling model, agricultural robot, experiment verification

Introduction
The hilly and mountainous areas account for about one-third of land areas in China. According to statistics, more than 55% of the grain output is produced in the hilly and mountainous areas. Agricultural economy in these regions has enormous potential for development. Taking Chongqing city as an example, the farmland with a slope greater than 5° accounts for 55.22% of the total farmland area. With the accelerated urbanization and the increasing shortage of rural labor, agricultural mechanization is an inevitable way for the sustainable development of agriculture. However, due to the complex terrain, small fields, and numerous steep slopes in hilly and mountainous areas, conventional agricultural robots have encountered...
so many problems such as low operating efficiency, poor working quality, and low safety.7,8 More than 75% of the agricultural machinery used in the plains cannot be employed in hilly mountainous areas due to the large slope of farmland.9 Take harvesting machinery as an example, as the weight of the grain box increases, the gravity center of the whole machine will shift if it is driven on a ramp. It may cause the harvester to operate less efficiently and even have rollover accidents. In addition, the operation quality of the threshing mechanism of the harvester is seriously decreased when it cannot be kept horizontal. The agricultural production in the hilly and mountainous areas is still dominated by traditional small machinery and human and animal power.10-12 The level of comprehensive agricultural mechanization in hilly and mountainous areas was 46.87% in 2018, which was 21.92% lower than the national average.13 The auto-adaptive leveling hydraulic suspension for the agricultural robot may be helpful to increase the mechanization rate.

Agricultural robots in hilly and mountainous areas are not only needed to improve passing ability but also required to focus on adaptability for complex terrain.14 In the past, mechanical leveling mechanism was often employed, which is composed of leveling spring and connecting rod. This is a passive leveling system, which can be used for applications with small adjustment range and low sensitivity requirements.15,16 The interconnected leveling suspensions with electrohydraulic actuators as actuating elements are also adopted. The interconnected leveling suspension can only be adjusted in one direction.17 It may become less effective when the chassis is driven on continuously undulating road surface.

One study invented a new kind of dynamic leveling agricultural chassis for hilly and mountainous areas.18 Reza et al. designed an interval type-2 fractional-order fuzzy controller for a tractor active suspension system. The conclusions revealed that the proposed controller makes outstanding yield in comparison to other controllers in the presence of road disturbances.19 Ding et al. studied an active hybrid electromagnetic suspension, which can achieve body leveling of low-power machinery.20 An electromagnetic damper was designed as an active actuator which is comprised of a permanent magnet direct current motor and a ball screw.21 Jin et al. studied a new posture-controlled chassis of caterpillar combine which can achieve satisfying results when the slope angle is not greater than 5°.22 The global sensitivity analysis and multiobjective optimization of a new hydraulic interconnected suspension were conducted by Zhang et al. As results, the root-mean-square value of pitch angular acceleration decreased by 12.95%.23 However, the research to date has not been able to develop an auto-adaptive leveling hydraulic suspension for hilly and mountainous areas, which has a lot of advantages such as simple structure, large power, easy to control, and large adjustment ranges.

Previous studies have the following limitations. Firstly, the mechanical structure was mostly adopted in the adaptive leveling suspension, which has some problems, such as small adjustment range and low precision. Secondly, hydraulic interconnected suspension was a research hotspot in the past. This type of suspension can only achieve leveling when the vehicle is driving on the ramp. It does work on the continuously undulating road. Thirdly, the pressure compensation system is not adopted on the existing hydraulic suspension, which makes it difficult to control the speed of the actuator. All the above problems have been solved in the research of this article.

To improve the suitability of large agricultural machinery in hilly mountainous areas, a new auto-adaptive leveling hydraulic suspension, which can be adopted for leveling on slope and continuously undulating road, was analyzed and developed in this study. The adjustment range is determined by the hydraulic cylinder stroke, the mechanical structure, and the machine wheelbase. But the general adjustment range is not less than ±7.5°. Since hydraulic components can be applied to large loads, this hydraulic suspension can be used for auto-adaptive leveling of large agricultural equipment.

The remaining part of the article is organized as follows: The hydraulic system scheme of auto-adaptive leveling hydraulic suspension and its controlling model are presented in the second section. Then the load-sensing system is modeled and simulated in the third section. The experimental results are given in the fourth section to verify the auto-adaptive leveling effectiveness. Finally, the concluding remarks of this study are described in the fifth section.

**Design of auto-adaptive leveling hydraulic suspension**

Hydraulic systems are chosen due to a series of advantages such as high power density and fast effect speed. The hydraulic system was reasonably designed to meet the operation requirements of hydraulic suspension. The control model was constructed and its feasibility and rationality were verified.

**Design of hydraulic system scheme**

The schematic diagram of the designed hydraulic system is shown in Figure 1. The engine is the power source of the hydraulic system, and the load-sensing pump, whose output flow rate always matches the flow requirement of the system, is used as the power element. The load-sensing pump outlet is connected to four branches. Each branch is a pressure compensation system composed of a fixed differential pressure reducing valve and a shuttle valve, which is utilized to maintain the pressure difference between the inlet and outlet of the three-position four-way proportional directional valve, does not change with the load.
The three-position four-port proportional directional valve has dual functions of speed regulation and direction change, and its spool opening is given by the control signal. The hydraulic controlling one-way valve is utilized to lock the hydraulic cylinder. Safety valve is used to set the safe pressure of the system. When the working pressure exceeds the safe pressure, the safety valve will be opened to unload. Maximum load capacity is limited by hydraulic cylinder size and maximum pressure. The theoretical maximum thrust is greater than 28000 N for the hydraulic cylinder with piston diameter of 60 mm and the rated pressure of 10 MPa. Therefore, hydraulic suspensions can be used for leveling for most heavy agricultural machinery.

The flow through the variable orifice can be calculated according to the following equation

\[ Q = C_q A \sqrt{\frac{2|\Delta P|}{\rho}} \]  

where \( Q \) is flow rate, \( C_q \) is flow coefficient, \( A \) is orifice cross-sectional area, \( \Delta P \) denotes the pressure difference between upstream and downstream, \( \rho \) denotes oil density.

If the opening of variable orifice is constant, the flow rate is directly proportional to one-second of the pressure difference between the upstream and downstream of the variable orifice, and if the pressure difference is maintained, the flow rate is only directly proportional to the variable orifice opening area. When agricultural machinery operates in the field, due to poor road conditions and slopes, the gravity center will be shifted in real time. As a result, the external load of each hydraulic cylinder is different. The pressure compensation system ensures a constant pressure difference between upstream and downstream of variable orifice and overcomes the disadvantage that the flow rate is difficult to control owing to the load change of the actuators.

This hydraulic system has the following advantages: (1) The load-sensing pump can automatically adjust its displacement according to the flow rate demand without generating excess flow rate. That means the system has low heat generation and high efficiency. (2) The pressure compensation system can ensure that the flow rate of the three-position four-way proportional directional valve is only proportional to the throttle opening when the load pressure changes. Load pressure refers to the external force that determines the working pressure of the hydraulic actuator. That means the system has high control accuracy. (3) The three-position four-port proportional directional valve has dual functions of speed regulation and direction change. The designed hydraulic system reduces the number of controlling valves and decreases the pressure loss effectively.

**Establishment of controlling model of hydraulic system**

Symmetric valve and asymmetric hydraulic cylinder system displayed in Figure 2 are used in hydraulic suspension.
Figure 2. Symmetric valve and asymmetric hydraulic cylinder system.

To study the dynamic characteristics of the system, a controlling model of the hydraulic system is established.

The flow rate continuity equation of the rodless cavity and rod cavity of the hydraulic cylinder is shown in the following equations:

\[
q_1 = \frac{dV_1}{dt} + \frac{V_1}{\beta_c} \frac{dp_1}{dt} + C_{ec}p_1' + C_{ic}(p_1' - p_2') \tag{2}
\]

\[
q_2 = -\frac{dV_2}{dt} - \frac{V_2}{\beta_c} \frac{dp_2}{dt} - C_{ec}p_2' + C_{ic}(p_1' - p_2') \tag{3}
\]

Loading flow rate can be calculated according to the following equations:

\[
q_L = \frac{(A_1 + A_2)}{2} \frac{dv}{dt} + \frac{V_0}{2\beta_c} \left( \frac{dp_1'}{dt} - \frac{dp_2'}{dt} \right) + \left( \frac{C_{ec}}{2} + C_{ic} \right)p_L \tag{4}
\]

\[
p_L = p_1' - np_2' \tag{5}
\]

\[
n = \frac{A_1}{A_2} \tag{6}
\]

In equation (2) to (6), the meaning of each parameter is shown in the following. \(q_1\) denotes rodless cavity flow rate. \(q_2\) denotes rod cavity flow rate. \(q_L\) is loading flow rate. \(V_1\) is rodless cavity volume. \(V_2\) is rod cavity volume. \(p_1'\) is rodless cavity pressure. \(p_2'\) is rod cavity pressure. \(A_1\) is effective areas of rodless cavity. \(A_2\) is effective areas of rod cavity. \(\beta_c\) is volume elastic modulus of hydraulic oil. \(C_{ec}\) is external leakage coefficient of hydraulic cylinder. \(C_{ic}\) is internal leakage coefficient of hydraulic cylinder.

The following equations can be deduced from the load flow rate definition:

\[
K_{q1} = c_d\omega \sqrt{\frac{2(p_s - p_L)}{\rho(1 + n^3)}} \tag{7}
\]

\[
K_{c1} = c_d\omega \sqrt{\frac{2(p_s - p_L)}{\rho(1 + n^3)}} \left( 2p_s - 2p_1 \right) \tag{8}
\]

where \(K_{q1}\) is flow rate gain. \(K_{c1}\) is pressure gain. \(c_d\) is flow coefficient. \(\omega\) is slide valve areas gradient. \(p_s\) is supply pressure and its value is the greater of \(p_1'\) and \(p_2'\). \(\rho\) is oil density. \(x_s\) is spool displacement.

The force balance equation of the hydraulic cylinder is shown as follows:

\[
A_1p_1' - A_2p_2' = m\frac{d^2y}{dt^2} + B_c\frac{dy}{dt} + Ky + F \tag{9}
\]

where \(m\) is loading mass. \(B_c\) is damping ratio and \(F\) is disturbing force.

The values of each parameter of the above formulas are listed in Table 1.

The transfer function of the system shown in the following equation can be derived from the Laplace transform of the above equations:

\[
G(s) = \frac{Y(s)}{X_s} = \frac{K_{q1}}{\frac{(A_1 + A_2)}{2}s + \left( \frac{V_1}{4\beta_c} + \frac{V_0}{2}\frac{1 + n^2}{\rho s} + C_T + K_{c1} \right) \left( 1 + n^3 \right) \left( m^2 + B_c, s + K_y \right)} \tag{10}
\]

The dynamic property and stability of the designed hydraulic system were analyzed by MATLAB software. The Bode diagram and step response are shown in Figures 3 and 4. It can be demonstrated from Figures 3 and 4 that amplitude margin and phase margin are 3.78 and 13.5, respectively. The rising time is 1.85 s and the setting time is 3.31 s. Based on control theory, the system is stable when the amplitude margin and phase margin exceed 1. Therefore, the designed system has good stability and strong anti-interference ability.

### Simulation analysis

During the operation of agricultural robot in hilly and mountainous areas, the auto-adaptive leveling hydraulic suspension is required to direction change and speed

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Effective areas of rodless cavity pressure | \(A_1\) | 1.01787e-3 \(m^2\) |
| Effective areas of rod cavity pressure | \(A_2\) | 7.63407e-4 \(m^2\) |
| Rodless cavity pressure | \(p_1'\) | 5.06e6 Pa |
| Rod cavity pressure | \(p_2'\) | 2.0e5 Pa |
| Flow coefficient | \(c_d\) | 0.61 |
| Slide valve areas gradient | \(\omega\) | 0.237 |
| Oil density | \(\rho\) | 860 kg/m³ |
| Volume elastic modulus of hydraulic oil | \(\beta_c\) | 6.85e8 |
| External leakage coefficient of hydraulic cylinder | \(C_{ec}\) | 0 |
| Internal leakage coefficient of hydraulic cylinder | \(C_{ic}\) | 3e-11 |
| Loading mass | \(m\) | 500 kg |
regulation frequently due to the undulating ground. If the fixed displacement pump is used, the temperature of the hydraulic oil may be too high. This may affect the performance of the hydraulic system seriously. In addition, agricultural machinery will cause different working loads of each hydraulic cylinder owing to the carried cargo location and the undulating ground, which may cause problems such as uncontrollable hydraulic oil flow rate. So the flow will be difficult to control precisely in this case. To avoid the above problems, a load-sensing system of pump controlled was designed, which has a superior power following ability. The pressure and flow provided by the load-sensing pump match load requirements at any time.

**Modeling and simulation of load-sensing systems**

Advanced Modeling Environment for SIMulation (AMESim) software (homepage: https://www.plm.automation.siemens.com/global/zh/products/simcenter/simcenter-amesim.html) developed by Siemens is used for modeling and simulation of complex systems in multidisciplinary areas. The load-sensing system model presented in Figure 5 was established in the AMESim. The established model is composed of five main components. The load pressure simulation components change opening pressure by adjusting the electrical signal. The pressure relief component is used for ensuring safety when the pressure is excessive. The load pressure simulation components change opening pressure by adjusting the electrical signal. The pressure relief component is used for ensuring safety when the pressure is excessive. The load pressure simulation components change opening pressure by adjusting the electrical signal. The pressure relief component is used for ensuring safety when the pressure is excessive. 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**Figure 3.** Bode diagram.

**Figure 4.** Step response.

**Figure 5.** Simulation model of load-sensing system in AMESim software. 1—load pressure simulation components, 2—pressure relief component, 3—load-sensing components, 4—adjust components, and 5—orifice. AMESim: Advanced Modeling Environment for SIMulation.
adjusting components according to the real-time feedback data. In the simulation model, the pressure compensator is built by designing hydraulic submodules. The load pressure is simulated by a proportional relief valve whose opening pressure is controlled by a segmented function. The simulation time is 10 s and calculation step is 0.1 s. The curves of load pressure and flow are shown in Figure 6. The pressure change curves of the throttle inlet and outlet are shown in Figure 7.

It can be observed in Figure 6 that the load pressure changes uniformly from 0 bar to 100 bar within the period of 10.0 s. During this process, the flow rate through the orifice is always maintained at 29.65 L/min. Figure 7 reveals that the pressure at the oil inlet rises from 42.5 bar to 141.9 bar and the pressure at the oil outlet rises from 0 bar to 100.6 bar during the uniform rise of load pressure. The simulation results demonstrate that the load-sensing system can always keep the pressure difference between the throttle inlet and outlet constant when the load pressure changes. The flow is only proportional to the opening of the orifice and not has anything to do with the load. The designed load-sensing system has no redundant flow and has the advantages of superior power tracking, high control accuracy, and high efficiency.

**PID parameters optimization**

Proportional–integral–derivative (PID) control algorithms are adopted to further improve the control accuracy. The proportional coefficient, integral time constant, and differential time constant are usually taken empirically. The optimal combination of PID parameters was calculated by the optimization algorithm in AMESim. It should be noted that when the system parameters are set, this is a process that is automatically calculated by the program.

The maximum overshoot and rise time are used as evaluation indicators. The maximum overshoot is the error between the peak value and the target value and rise time is the time that the system rises from 0 to the target value firstly. The value range of the three parameters is shown in the following equation

\[
\begin{align*}
P & \in [0, 100] \\
I & \in [0, 10] \\
D & \in [0, 2]
\end{align*}
\]

The results advice that when the proportionality coefficient, integral time constant, and differential time constant are 21.827, 1.862, and 0.037, respectively, the control characteristics are optimal.

**Experiment of auto-adaptive leveling hydraulic suspension**

The experimental bench of auto-adaptive leveling hydraulic suspension is manufactured to verify the effectiveness. The experimental bench has two floors. The lower floor is used to simulate ground fluctuation with four hydraulic cylinders and the upper floor is the designed hydraulic suspension.

**Experiment bench development**

The mechanical principle of the experiment bench is shown in Figure 8. The main geometric parameters are marked in the figure. The number of hydraulic cylinders is 4. The upper and lower ends of each hydraulic cylinder are articulated. A center universal hinge is arranged in the middle of the four hydraulic cylinders. Theoretically, the frame can rotate around any axis, but the rotation angle is limited by the hydraulic cylinder stroke and the articulation mechanism. The maximum thrust force of each hydraulic cylinder is 12566 N.

A dual-axis inclinometer whose measurement range is from −90° to 90° is installed in the center. The experimental bench is shown in Figure 9, and the hydraulic power station is shown in Figure 10.

**Controlling strategy design**

The dual-axis inclinometer is used to determine the attitude of the frame. The controller outputs four analog quantities
to the proportional valve via the amplifier. The position and speed of each hydraulic cylinder are controlled by closed-loop control to improve the control accuracy. The load pressure can be continuously varied between 0 MPa and 10 MPa. The optimal PID parameters obtained in AMESim are adopted. At the same time, the output signal of the angle sensor is transmitted to the Smacq 3132 data acquisition card via an isolated transmitter. Data acquisition card parameters are presented in Table 2. Maximum stroke of each hydraulic cylinder is 20 cm and the stroke of each hydraulic cylinder is 10 cm at the initial state. When the stroke is in the range of −10 cm to 0 cm, it indicates that the hydraulic cylinder is in the extended state. When the stroke is in the range of 0 cm to 10 cm, it indicates that the cylinder is in the retracted state. Controlling strategy is displayed in Figure 11.

Experiment results

The upslope, downslope, side slope, and continuous undulating roads are simulated by the lower structure of the experiment bench, respectively, to verify the effectiveness of the auto-adaptive leveling hydraulic suspension. The actual loads are simulated by controlling the different opening pressure of four proportional relief valves. Loads changes of the four hydraulic cylinders are shown in Figure 12. The experiment results are shown in Figure 13.
The leveling effect under the upslope condition is shown in Figure 13(a). The maximum pitching angle when the leveling system is not in operation is $10.15^\circ$ and the maximum pitching angle when the leveling system is in operation is $0.87^\circ$. The leveling effect under the downslope condition is shown in Figure 13(b). The maximum pitching angle when the leveling system is not in operation is $9.99^\circ$ and the maximum pitching angle when the leveling system is in operation is $0.58^\circ$. The leveling effect underside slope conditions can be seen from Figure 13(c). When the leveling system does not work, the maximum positive tilting angle is $7.54^\circ$, and the maximum negative tilting angle is $-9.01^\circ$. When the leveling system works, the maximum positive tilting angle is $0.52^\circ$ and the maximum negative tilting angle is $-0.45^\circ$. The pitching angle curves of driving on a continuously undulating road are displayed in Figure 13(d). When the leveling system does not work, the maximum positive and negative elevation
angles are 1.84° and −1.87°, respectively. When the leveling system works, the maximum positive and negative pitching angles are 0.86° and −0.93°, respectively. The tilting angle curves of driving on a continuously undulating road are displayed in Figure 13(e). When the leveling system does not work, the maximum positive and negative tilt angles are 2.17° and −1.38°, respectively. When the leveling system works, the maximum positive and negative tilt angles are 0.97° and −0.83°, respectively. The experimental data illustrate that the developed auto-adaptive leveling hydraulic suspension, which can realize dynamic adjustment and maintain the level of the frame, meets the requirements in hilly and mountainous areas.

Discussion

A new auto-adaptive leveling hydraulic suspension for the agricultural robot was analyzed and designed in this article. Compared with previous studies, there are three innovations in this research. Firstly, the hydraulic suspension for the agricultural robot designed in this study has a wide adjustment range. The adjustment range of mechanical leveling suspension in Reference 18 is ±5° and that of this hydraulic suspension can exceed ±10°. In addition, the proposed scheme in this article has better auto-adaptive leveling accuracy. The maximum error of the designed hydraulic suspension is 0.97°, but the leveling mechanism error in Reference 18 is no less than 1.1°. Secondly, different from the hydraulic interconnected suspension, the hydraulic suspension can realize the leveling function and no matter the wheels are running on the ramp or the continuous undulating road surface. Thirdly, the pressure compensation system which can ensure that the flow rate of the hydraulic actuators can be accurately controlled is adopted in this hydraulic suspension. Beyond that, the suspension proposed in Reference 21 is not

Figure 13. Leveling effect of experiment bench. (The red-dotted line represents the tilting or pitching angle when the leveling system is not in operation and the solid green line represents the tilting or pitching angle when the leveling system is in operation). (a) Upslope condition, (b) downslope condition, (c) side slope condition, (d) pitching angle of driving on a continuously undulating road, and (e) tilting angle of driving on a continuously undulating road.
suitable for heavy load. The maximum load force is often not more than 7500 N. But the maximum thrust force of each hydraulic cylinder is 12566 N in this article.

**Conclusions**

The project was undertaken in this article to solve agricultural robot problems in hilly and mountain areas such as easy tilt of frame and low driving safety, so the agricultural auto-adaptive leveling hydraulic suspension was designed. The conclusions of this study are as follows.

1. The hydraulic system scheme of auto-adaptive leveling hydraulic suspension was developed according to the requirements of agricultural robots in hilly and mountainous areas. The controlling model of hydraulic system was established and the Bode diagram (Figure 3) and step response (Figure 4) illustrate that the designed system has good stability and strong anti-interference ability. The vehicle attitude information is measured by using a two-dimensional angle sensor and then four hydraulic cylinders are controlled to achieve dynamic leveling of the frame. This solution can improve the adaptability and passing ability of agricultural robots effectively in hilly and mountainous areas.

2. Load-sensing system was developed in the hydraulic suspension. The principle of the load-sensitive system is analyzed and then the load-sensitive system is modeled and simulated in the AMESim software. The simulation results (Figures 6 and 7) reveal that the flow rate is only related to the opening of the orifice and has nothing to do with the load. The designed load-sensing system has the advantages of superior power tracking, high control accuracy, and high efficiency.

3. The experimental bench of auto-adaptive leveling hydraulic suspension and its control system was established and the Bode diagram (Figure 3) and step response (Figure 4) illustrate that the designed system has good stability and strong anti-interference ability. The vehicle attitude information is measured by using a two-dimensional angle sensor and then four hydraulic cylinders are controlled to achieve dynamic leveling of the frame. This solution can improve the adaptability and passing ability of agricultural robots effectively in hilly and mountainous areas.

4. The experimental bench of auto-adaptive leveling hydraulic suspension and its control system was established and the Bode diagram (Figure 3) and step response (Figure 4) illustrate that the designed system has good stability and strong anti-interference ability. The vehicle attitude information is measured by using a two-dimensional angle sensor and then four hydraulic cylinders are controlled to achieve dynamic leveling of the frame. This solution can improve the adaptability and passing ability of agricultural robots effectively in hilly and mountainous areas.

5. The experimental bench of auto-adaptive leveling hydraulic suspension and its control system was developed to evaluate the leveling effectiveness. The experimental results demonstrate that the auto-adaptive leveling hydraulic suspension can adjust the frame levelness dynamically on upslope, downslope, side slope, and continuous undulating roads. The maximum errors in pitching and tilting angles are $-0.93^\circ$ and $0.97^\circ$, respectively. The research methods in this article can provide theoretical basis for the design of other auto-adaptive leveling systems in hilly and mountain areas.

**Declaration of conflicting interests**

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**ORCID iD**

Kai Hu https://orcid.org/0000-0002-9254-6144

**Supplemental material**

Supplemental material for this article is available online.

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